BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 69(4), 2021, Article number: e137725
DOI: 10.24425/bpasts.2021.137725

SPECIAL SECTION

Microscopic simulation of pedestrian traffic in urban environment under epidemic conditions

Mateusz PACIOREK[1*], **Damian POKLEWSKI-KOZIEŁŁ**[2], **Kinga RACOŃ-LEJA**[2], **Aleksander BYRSKI**[1], **Mateusz GYURKOVICH**[2], **and Wojciech TUREK**[1]

[1] AGH University of Science and Technology, al. Adama Mickiewicza 30, 30-059 Krakow, Poland
[2] Cracow University of Technology, ul. Warszawska 24, 31-155 Krakow, Poland

Abstract. The ongoing period of the pandemic makes everybody focused on the matters related to fighting this immense problem posed to the societies worldwide. The governments deal with the threat by publishing regulations which should allow to mitigate the pandemic, walking on thin ice as the decision makers do not always know how to properly respond to the threat in order to save people. Computer-based simulations of e.g. parts of the city or rural area should provide significant help, however, there are some requirements to fulfill. The simulation should be verifiable, supported by the urban research and it should be possible to run it in appropriate scale. Thus in this paper we present an interdisciplinary work of urban researchers and computer scientists, proposing a scalable, HPC-grade model of simulation, which was tested in a real scenario and may be further used to extend our knowledge about epidemic spread and the results of its counteracting methods. The paper shows the relevant state of the art, discusses the micro-scale simulation model, sketches out the elements of its implementation and provides tangible results gathered for a part of the city of Krakow, Poland.

Key words: epidemic modeling; pedestrian dynamics simulation; urban environment.

1. INTRODUCTION

The pandemic of Covid-19 stimulated research on the relationship between the possible spread of the virus and urban form. Architectural and urban aspects find their reference in contemporary scientific research, becoming a complementary trend for medical activities in the process of protecting city residents from the possible harmful effects of a pandemic. The cities change constantly, adapting to the needs and the level of technology of the societies, as well as to the newest ideas. Unlike in historic times, there is no one, most popular model of the city, which could be universal (like "roman city", "industrial city", "funcionalist city" etc.) [1, 2]. Therefore, the paradigm of the contemporary city of the 21st century is still one of the most discussed issues among architects, urban planners, sociologists and specialists from many different fields all over the world [3–7]. Even now, it is hard to establish if we need to focus more on eco, smart, dense or resilient cities, since in some points this terms are contridactory. Especially when taking under consideration the resilience of the city to contemporary natural and man-made threats, the fast development of new technologies and the density of urban tissues, might be understood as obstacles. The traditional typologies of urban buildings and complexes are changing and constantly evolving, introducing new hybrid models in which different functions are mixed within one object or complex. Furthermore the public space of the city overlaps with the interiors on different levels, offering new platforms for social contacts [8]. The evolution and diversity of forms and functions of city blocks, which builds urban fabric is also the factor of the abovementioned change [9, 10]. As in most countries, the majority of Poland's population (over 60% in 2019) lives in cities, urban functional areas and emerging metropolitan areas [11]. As proven by all the history of urbanization, such concentration of citizens in a relatively small area [9], is beneficial for economic, sociological and cultural reasons under normal conditions. Density and concentration are the main factors, which differed the cities from village areas from the very beginning [1]. But it turns out to be at the same time dangerous in the face of man-made and natural disasters, including wars [12], terrorist attacks and epidemics, which are also defined as "megatrends" [5]. Some research [13] and available data [14] proves, that cities with the greatest urban and demographic structure densities and that have significant position in the global inter-city linkage network, are the most susceptible to them. This position can aid the rapid spread of global phenomena, including these with adverse effects. The contemporary social structure is considered by many to be a network society, and is therefore subjected to many rules that define the functioning of other networks [15]. However, sometimes, the diversification of urban structures, together with smart technologies, might make some cities more resilient than others [5]. New rules of functioning during pandemics and in post-pandemic times should be established for global networks, as well as the networks within cities and towns [16]. Computer simulations can be very helpful in this process.

*e-mail: mpaciorek@agh.edu.pl

Manuscript submitted 2020-12-17, revised 2021-04-14, initially accepted for publication 2021-05-15, published in August 2021

The degree to which Poland is urbanized maintains values considered average for Europe. One of its distinct features is the large share of medium- and small-sized cities [17, 18]. They are typically located near each other, particularly in the south of Poland [19]. The development and growth of Poland's cities over the past century has led to a diversification of their tissue. Within the administrative limits of cities all over Europe, we can observe fragments of composed urban tissue with diverse spatial layouts that are typically the result of historical considerations, as noted by many scholars [20, 21]. In Polish cities, prefabricated housing block estates built in the second half of the 20th century still occupy large areas. They are accompanied by their new, "developer" versions, mostly much more defective in terms of the correctness of their urban form and functional layout [22]. Single-family housing complexes are a supplementation of this structure. Many of them were built on the basis of the spatial layouts of former villages that had been incorporated into cities [23]. Due to the rather chaotic structure of Polish cities that has been heavily impacted by historical and socio-economic processes of the previous century: wartime destruction, communism, and the sudden and practically uncontrolled development of urban structures in the first decades of the 21st century, it is very difficult to form spatial structure models for existing cities. The main difficulty in creating such a model is the mix of urban typologies and spacial chaos, which is characteristic particularly for Polish cities and towns due to the unsustainable development in the last four – seven decades [24]. In spite of this, attempts at building virtual models have continued to be made, both worldwide [25], and in Poland [26]. Within them, diverse fragments of tissue are characterized by different morphologies and urban compositions [27], and therefore generate different circulatory behaviors. This refers to pedestrian circulation in particular, as the density of the network of services necessary for the proper functioning of society within its housing environment should be located mainly within the pedestrian reach of 15–20 minutes of walk (250–400 m). However, within topologically diverse fragments of urban tissue the location of basic services is also different. As shown by the experience of recent months, this is a key problem during a pandemic, as the network of pedestrian public spaces and their form and typology can turn out to be inadequately suited to the changing needs.

In order to examine the features of the existing pedestrians traffic infrastructure under epidemic conditions, we decided to join efforts of urban planning experts and computer scientists. In this work we describe a method for studying the relations between the urban tissue structure and the possibility of preserving social distances, by means of a large-scale computer simulation. The simulation uses a discrete, microscopic model of the urban environment and adopts the agent paradigm in order to reflect detailed behaviors of individuals, their interactions and interactions with the environment. The proposed method allows estimating the number of social distance violations and identification of locations, which cause the violations.

The main contributions of the work are:

- design of a microscopic simulation model dedicated to representing details of urban infrastructure for pedestrians, considering flexible patterns of pedestrian mobility, types of pedestrians, social distance motivations and metrics for their violations,
- proposal of a method for importing the environment models from available sources,
- proposal of a method for collecting data of pedestrian mobility patterns from real housing estates,
- proposal of an efficient simulation algorithm, which allows to perform statistical analysis of results,
- preliminary validation of the model,
- discussion of simulation results for a representative housing estate.

The following sections of this paper present existing approaches to the problem of microscopic pedestrian dynamics modeling in epidemic conditions, the proposed model, the method for building the model of a selected housing estate, simulation results and their discussion.

2. EXISTING APPROACHES

2.1. Microscopic pedestrian dynamics modeling

The problem of pedestrian dynamics computer simulation has been studied for many decades. Pedestrian motion, crowd dynamics and building evacuations attracted enormous attention – it has a dedicated conference (International Conference on Pedestrian and Evacuation Dynamics) and several surveys can be found [28–30]. In recent years the vast majority of research focus on microscopic models and agent-based simulations, which distinguish individual entities and allow differences in their characteristics and behavior. This feature is necessary in the problem considered in our work.

There are numerous methods for modeling motivations of simulated agents. Widely used approaches include variants of social force, magnetic force and benefit-cost [31]. All solutions represent similar desire to move towards the goal and differ in methods of representing proxemics rules. It seems that the majority of the existing models might be adopted for representing social distancing observed during the current epidemics.

Another decision, which has to be made while defining the simulation model, is the representation of the environment. In the vast majority of pedestrian simulations, the environment is two-dimensional, which has been discussed in [32]. The simulated surface can be continuous, however, many researchers find discretization suitable for their needs [33]. It allows efficient simulation of large environments while preserving sufficient expressiveness.

The above-mentioned efficiency is the common challenge identified in many publications in the area. There are at least four factors which collectively support the demand for high performance pedestrian dynamics simulations: need for representing large environments, complex, detailed models, desire to collect results fast and the need for repetitions due to the stochastic nature of the models. Satisfying these needs using a single computer is hardly possible, therefore effort is being put into developing algorithms for parallel model update [34].

Efficient parallelization of such tasks is not trivial. The simulation algorithm changes the state of a common data structure, therefore, concurrent read and write access to the data has to be supported by the algorithm. The simulations presented in this work are based on the original concept of signal-based information propagation, which has been used for building a distributed model update algorithm [35]. The algorithm has proven almost linear scalability on several thousands of computing cores of a High-Performance Computing (HPC) system. The details of the simulation algorithm applied to the considered problem of pedestrian motion in urban environment, will be provided in Section 3.

2.2. Epidemic spread modeling and simulation

The ongoing pandemic of Covid-19 triggered enormous number of research on epidemic models. More than 10% of all papers related to "epidemic modeling" have been published in the current year, 2020, according to online search engines of arXiv, IEEE Xplore, ScienceDirect and Web of Science. The majority of recent research presents a macroscopic approach, considering the dynamics of large populations. These works typically use variations of the well-established Susceptible-Infected-Recovered (SIR) model [36].

In the specific problem considered in our work, the macroscopic, system dynamics approach cannot be directly applied. It turns out that very few of the contemporary researches consider microscopic simulations and detailed interactions between individuals. One of the reasons is probably the complexity of the model and the amount of work required for its calibration.

The concept of using microscopic simulations in disease spread modeling is not novel – in work of Fuentes and Kuperman [37] published in 1999 propose a simple cellular automation for analyzing the phenomena. Similar approach, presented recently in [38], considers a simple space and investigates parameters similar to SIR concept. Cellular automaton is also used in [39], where an attempt to model virus transmission using distance and direction of people is presented. Different modeling method is adopted in [40] where social force model is implemented for continuous space representation. The work also presents an infection model and analysis examples of indoor environment.

The identified approaches to the problem of microscopic simulation of epidemic spread are limited to small environments. Such environments can be interpreted as indoor spaces, where people gather in large numbers. The implementation of such models is relatively simple – limited space enables sufficient efficiency with sequential processing. Our team decided to go beyond these limitations and proposes a method for microscopic simulations of large scale environments, which can be used for investigating epidemic conditions in outdoor public spaces.

2.3. Research context of epidemic spread vs urban design

In modern research on the spread of the pandemic, spatial aspects emerge. We are aware that the Covid-19 pandemic has affected the patterns of using public and private spaces [41]. Social distancing can lead to a deepening of social differentiation because space becomes an element of luxury – both in terms of private and spatial areas [42, 43]. In terms of physical safety, the use of masks is an element that promotes anonymity in space, provoking anti-social behavior [42]. On the other hand, the digitization of social life becomes a factor influencing continuous surveillance of public spaces [42].

In the areas of open spaces, some authors look for solutions to details affecting public health. The ecosystem function of greenery, complementing urban density role gets essential in new post-pandemic urban landscapes [44]. M. Hanzl in the field of green infrastructure reflects the aspects of short-term interventions regarding the transformations of the street spaces, parking areas or temporary tools marking the place. The spatial interventions might direct the inner-city areas of Milan or Paris into the '15-minute cities' – with a quarter of an hour walking distance not only to primary services but also to green public and recreation areas [44].

M. Duarte Pineiro and N. Cardoso Luís at the general level indicate which elements influence the resilience and sustainability of the built environment in the pandemic period, referring to street paths, public equipment, public transport facilities, green areas as well as the buildings themselves depending on function [45].

The pedestrian and bicycle accessibility is a part of a pandemic adjustable city [44], walkability certainly becomes an aspect of the urban evaluation of the pandemic environment. Urban mobility in terms of daily and long travel during COVID-19 is discussed by M.R. Fatmi – regarding the pedestrian mobility frequency change in regards to work and recreation/activities researched and in relation to the age of the people [46]. A Qualitative Approach to the natural disasters risk reduction is discussed with regards to the walkability in the city, reflecting the average speed and pedestrian distance facing normal and evacuation situations [47].

The interesting interdisciplinary research of Centro Producción del Espacio was recently presented in the form of a cartographic atlas of indicators – revealing potentially dangerous (in regards to pandemic) city spaces. As valuable incorporation, the data included the location of older adults as the most vulnerable population or housing exposed by difficult socio-economic conditions [48].

Urban public areas, with pedestrian movement are presently the area of in-depth investigation. The possibilities of collecting data are differentiated, using all possible sources, research in this field is also carried out in the space syntax methodology. In the source studies presented here, one can still feel a certain deficiency with regard to virtual simulations of the possibilities of using urban spaces, which could become a virtual urban laboratory by modeling various variants of behavior. The area of this research should also find a reference to the characteristic urban and social typology of the urban structure and the group of inhabitants assigned to it. We adopted such assumptions for the implementation of the research presented in the article by our team. Research that is currently carried out around the world refers to specific urban environments, with a given community and its own cultural specificity – often different from the European one – which prompted our team to examine a representative housing estate for the middle class in Poland.

3. PEDESTRIAN DYNAMICS MODEL FOR DETAILED URBAN ENVIRONMENT

3.1. Pedestrian dynamics model

The method used to create the model used in this research is based on the concepts detailed in [35], which ensures good scalability. The modeled area is represented as a grid in which each cell is assigned a type corresponding to the terrain depicted by a given cell. The exact collection of available types is dependent on the analyzed environment, with most common examples being the roads, buildings, sidewalks or various types of greenery. The main application of the cell type is the assignment of a parameter, *walkability factor*, representing the eagerness of a person to enter the cell of that type. The value of this factor can range from 0, meaning that the cell type is impossible to enter (e.g. a building wall) or never chosen to enter (e.g. water stream), to 1, meaning that the cell type is designed to being used by pedestrians (e.g. sidewalk). This factor is essential in calculating the preferred paths to potential destinations for pedestrians.

The definition of possible destinations consists of the set of entries containing the following data:

- A set of coordinates of the entrances of the destination. In the case of the destination other than the building, a point at which a person is considered to have reached the destination is used in place of the entrance.
- A type or a set of types of the destination. Possible types depend on the data provided and can include services, residential places, workplaces, schools etc.
- Population of the destination. Applicable only to the destinations that serve as permanent residence of people (usually an apartment block or a private house).

The process of creating the paths is repeated for each destination. In each instance the entrances to the destination are assigned a signal source, which is then propagated throughout the grid as described in [35], with two important modifications:

- to allow the signal to bend around the obstacles and areas with low *walkability factor*, the signal is always propagated in both main direction and adjacent directions (the behavior originally restricted to the diagonal directions),
- the signal is additionally reduced by *walkability factor* of the cell it is passing through, to reflect pedestrian preferences.

After the signal is able to reach all cells in the grid, the state of the whole grid is saved as navigation data for given destination. Additionally, the mapping in each cell from the direction to the signal strength is reduced to just the direction that recorded the strongest signal. This step was dictated by the large volume of unprocessed data in the original form, while the final logic of the simulation required only the knowledge of the best direction from the given cell to reach the given destination. Therefore, this preprocessing of data reduced space usage and unnecessary repetitions of processing during simulation.

The behavior of modeled people comprises three stages: creation, selection of the destination and navigation.

In order to accurately represent the people exiting the apartments, the model requires the knowledge of the distribution of people exiting residential buildings, depending on the population of the building and the time of day. The details on obtaining such data are presented in Section 4. By combining this data with the population of each building and the in-simulation time, in each iteration every residential building entrance cell is deciding randomly whether another person should appear in the grid.

Each newly created pedestrian is assigned a destination type, according to the distribution given as another input data, dependent on the time of day. Based on the selected type, specific destination is selected from the destination points that include this type in their definition. Additional rules may apply, e.g. the destination is selected as the closest one instead of random. A special type of destination representing strolling behavior is available, in which person does not have a final destination and instead periodically changes targets, to emulate erratic behavior of wandering.

Finally, the pedestrians begin the process of navigation towards the selected destination. In addition to the position of the pedestrian, additional markers are created in the grid, representing the vicinity of the person. Markers are allowed to spread in all directions until they reach predefined distance from the origin. This spreading occurs several times for each movement of pedestrians. Markers contain information which person they belongs to, how far they have spread from the point of creation and from which direction they have spread to the given cell. If several markers from the same person appear in the cell, only the ones with lowest distance to the origin are kept. The main role of the markers is to allow detection of social distance violations. If a person enters the cell containing the marker belonging to another person, with distance to source lesser than the predefined threshold, the violation is registered. The direction of pedestrian movement in each iteration is chosen accordingly to the navigation data created prior to the execution of the simulation, as shown in Fig. 1A. Additionally, social avoidance can be enabled in the simulation settings, modifying slightly this algorithm. If it is enabled, person will be allowed to choose the direction adjacent to the optimal one, if the current cell contains foreign markers (whether the violation was triggered or not) and their direction to source is the same as the optimal one. This choice depends on the distance to source, so that pedestrians in closer proximity are more eager

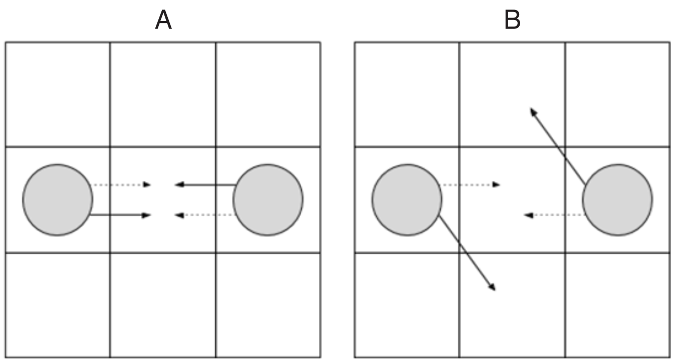


Fig. 1. Behavior of pedestrians in proximity to other pedestrians. Dotted arrows represent precalculated optimal directions, solid arrows represent the chosen movement direction. A: social avoidance disabled, B: social avoidance enabled

to avoid each other. Additionally, clockwise adjacent direction is always prioritized to avoid people stepping aside in the same direction. The emerging behavior is shown in Fig. 1B. As the avoiding maneuver may lead to the situation where people are unable to enter a narrow passage in a permanent cycle of side-stepping, each person possesses a short memory of previous decisions (i.e. coordinates of cell and chosen direction) and will avoid repeating the same decision unless no other decision is possible.

An important note pertaining to the use of the aforementioned markers is that their essential role is very similar to the one of the signal propagation. The main difference is that the signal does not possess its identity or other information, signal approaching from the same direction from several sources is added to a single value and, finally, signal is propagated indefinitely. On the other hand, markers are more akin to agents and allow to differentiate between a single person in near vicinity and multiple people in a distance, can be removed after they reach their maximal distance and allow the pedestrian to ignore their own vicinity. Therefore, this system has been used in this model, as a modified version of signal usually used in this modeling method.

3.2. Environment model: architectural plans handling

The simulation model requires data on the location of buildings, walkable areas and other points of interest. In order to create input data for the simulation model described in the previous subsection, the following requirements were established:

- The spatial resolution of the modeled area was chosen to be 1×1 m for each cell.
- Time step of the simulation was chosen to be 1 second.
- Distance threshold for social distance violation was chosen to be 1 m.
- Data must include a list of buildings with their types (e.g. service, residential etc.) which will be used to create a set of destinations, used in generation of navigation data and later in simulation to create pedestrians and choose their destinations.
- Data must include the distribution of people exiting buildings, which will be used to govern creation of agents representing pedestrians.
- Data must include the distribution of pedestrians destinations, which will be used to assign goals to the agents.

All of the requirements mentioned above serve as a foundation of the process that—in conjunction with the model—allows the translation from the chosen real environment to the simulation yielding the information regarding the locations potentially hazardous under the epidemic conditions.

3.3. Proposed validation method

The goal of the proposed model is to represent the collective, social behavior of pedestrians in public spaces of urban areas. It does not aim at reflecting accurately the behaviors of each singular person and each particular trajectory – which would be hardly possible. The detailed behaviors in real data may strongly vary between days, influenced by many random factors. Therefore, we decided that it is impractical to devise a method of validation based on fine-grained analysis, e.g. tracking and comparing the path taken by any single pedestrian.

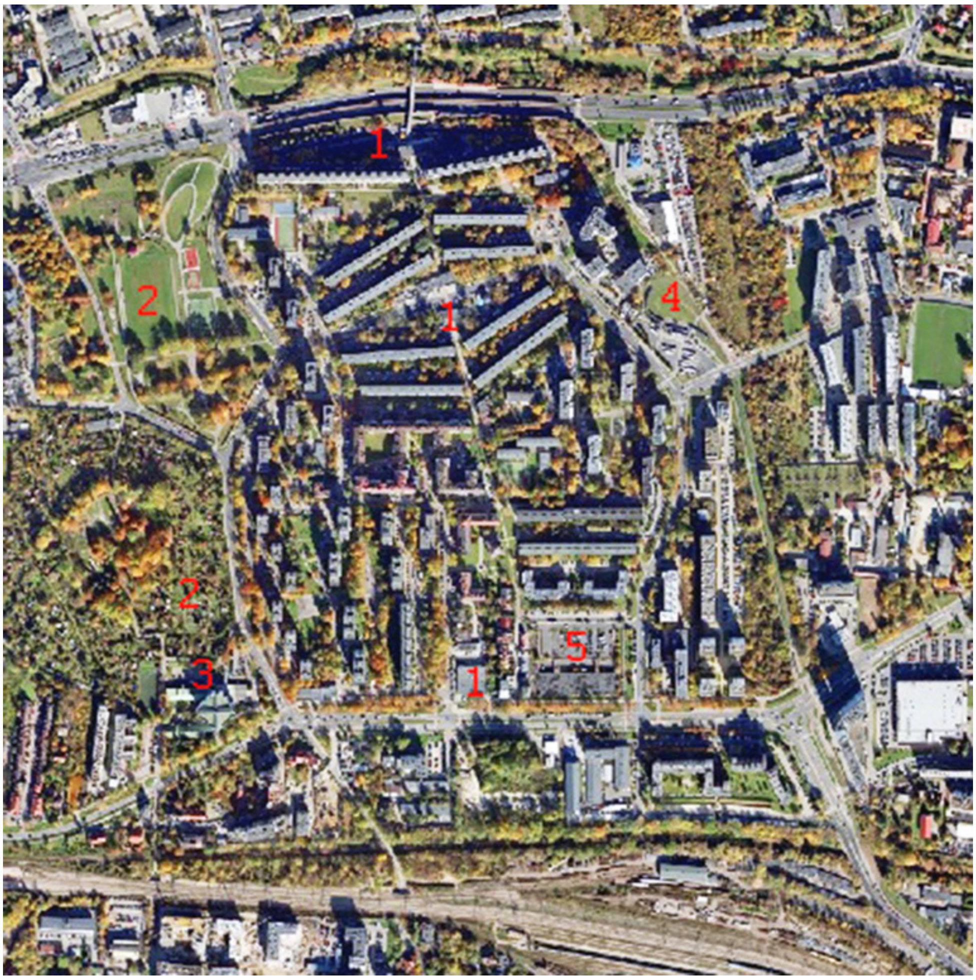
To achieve the goals defined in this work, the model should rather be able to generate motion plans using probability distributions and representing the stochastic nature of the phenomena. To validate the correctness of model results, the method that compares aggregated traffic intensity in selected areas in various times of a day is proposed. The validation of the model is inspired by research conducted by W. Whyte in the area of the quality of public space perceived in the observer's field of view in correlation with the number of people [49]. Therefore, the proposed method involved comparison of the aggregated number of people in the camera frame scope with the corresponding – in time and place – frames of the pedestrian movement simulation. The proposed aggregation of data from observations and simulation concerns periods with significantly different traffic intensity: morning peak, noon hours, afternoon peak and evening hours. The aggregated numbers of people for these periods in particular locations should correspond between the reality and the simulation and should differ between the periods.

4. REAL-LIFE DATA FOR MODEL CALIBRATION

4.1. Case-study: representative fragment of urban tissue

For the purposes of this research, a fragment of urban tissue that is distinctive for Polish cities was selected for analyses and modeling: a housing estate from the second half of the twentieth century. Such structures predominate in numerous Polish cities. It is estimated that around 25–40 per cent of households in large Polish cities inhabit housing blocks from this period [19, 50]. The Krowodrza Górka housing estate in Krakow was selected as a case study. It is a typical housing environment and is equipped with an array of essential services that ensure correct functioning in terms of everyday activities (stores, services, education, healthcare, sports and recreation). Most of these are of local significance. Apart from a branch of the Tax Administration, the complex does not include institutions or establishments that generate increased traffic, whether client- or tourist-based. This is why it is relatively easy to perform research on the transport behaviours of residents and other users there during the pandemic. The Krowodrza Górka housing estate has good circulatory connections with the city centre, both via the road network and public transport system (tram, bus, a nearby fast commuter rail stop).

The Krowodrza Górka housing estate is located in the north-western part of Krakow, in the northern strip of housing development that was built in the 1960s, relatively close to the city centre. The population density in the entire district of Krowodrza is over 90 persons/ha. However, the big amount of green areas and single-family development in the district makes, that in analysed area of housing estate this factor is much higher. The original urban composition of the housing estate, composed of single- and multi-stairwell multi-family residential buildings, is laid out in a highly distinctive pattern that forms heliotropic interiors [51]. This development is organised around a pedestrian path that runs diagonally across the



1 – groups of shops and serives on the crossing of main pedestrian foot path
2 – public parks
3 – parish church, school, sport and cultural center
4 – main tram and bus terminus
5 – main public parking lot

Fig. 2. The existing aerial photos shows the current layout of the Krowodrza Górka Housing Estate (as for autumn 2019); elaborated by authors on the basis of aerial photography from: https://msip.krakow.pl (accessed on May the 6th 2020)

complex and is oriented towards the Main Market Square and St Mary's Basilica in the distance, towards the southeast. This path ensures access to centrally located recreational green areas which include schools, kindergartens and a healthcare centre. The places where this path intersects with the road network include commercial and service complexes and administrative and cultural buildings. The complex borders to the west with two parks and allotment gardens of supralocal significance. To the south of the park complex, stands the Parish Church of St Jadwiga the queen, which was built in the early 1980s and is a leading architectural achievement of the period in Poland (designed by R. Loegler, J. Czekaj and associates) [52]. Over time, the parish became a basis for the establishment of a Catholic school and kindergarten, along with a dynamically operating culture and sports centre. To the east of the housing complex a tram and bus terminus is situated.

After 1989, the structure of the housing estate became denser, primarily in its southern section. Multi-family residential buildings were built, including a large complex on the estate's former recreational areas in the west and buildings in the immediate vicinity of the tram terminus. Numerous service pavilions were also built near major streets on the edges of the housing complex in the years 1989–2017. Along with the start of the twentieth century, the Gigant service centre, which was located along the southern edge of the estate, near a promenade, was destroyed in a fire. Since that time, the site has been serving as large parking lot, used by residents and clients of neighbouring services (including the Tax Administration Office). The increase of individual motorisation indicators since the 1990s was another factor that has contributed to the partial spatial degradation of the estate. In spite of this, the primary foot path still remains an important functional and spatial axis, particularly in the central part of the complex. Even though the number and significance of peripherally located service complexes that are accessible by both public transport and by car has increased.

4.2. Architectural and spatial data

Maps available on open source platforms like MSIP[1] or OpenStreetMap[2] could not be directly used due to the limited number

[1] https://msip.um.krakow.pl
[2] https://www.openstreetmap.org

of information they carry. Therefore, it was decided to use the up-to-date map obtained from geodetic resources, which was further manually detailed in such a way that each part of it could be a desired information database. First of all, it was necessary to clarify: the ways areas and buildings are used, places where entrances into the buildings and underground garages are located, on-site parking spaces for passenger cars, pavements, public squares, bike paths, public transportation stops, and pedestrian crossings. The intention was to create a map in which the color becomes a carrier of information, thus creating an easily defined environment for people movement simulations. For this purpose, a map key was developed that defined 40 different categories of land use patterns from which the final map was developed. Generated scope of different land uses is extensive enough to describe a wider range of areas. For further precise map conversion, the area in question, due to its size and the adopted mapping scale (1:200), was divided into 24 sections with a size of 1000×800 mm, and a resolution of 10000×8000 px, which corresponded to the actual area of 200×160 m. In this way, the desired accuracy of reproducing the reality was obtained, in which there were 50 pixels per one meter. Finally 24.png file format map sections were exported together with a code for merging them. (see Fig. 3). The sectioned and exported map has been downscaled so that the single cell represents area of 1×1m, as required by the model in terms of space and time resolution, resulting in a grid of dimensions 800×960 representing area of size 800×960 m. Mapping from the colors to terrain types allowed to assign types to the cells, chosen as the most prevalent color in the original region represented as the given cell.

4.3. Data on the number of people

Information about the number of people living in the area and individual buildings was obtained by 3D modeling of the buildings in a software using BIM technology. Modeling was carried out on the basis of the current CAD map supplemented by own photographic data and those commonly available on the Internet. The gross floor area (GFA) were assigned to four functional categories: residential, office, social (schools, kindergartens, libraries, cultural facilities), commercial (shops, services), for which two different indicators were then adopted to calculate the expected number of people: 30 m^2 of GFA/1 person for residential buildings and 35 m^2 of GFA/1 person for other buildings. Indicators constitute an input variable at the top of the calculation ladder, which, if possible to be verified on the basis of external statistical data, can be adequately adjusted (see Fig. 4).

4.4. Data on the number of people in motion

The number of people in motion was calculated on the basis of a commonly used method in research on public life studies, i.e. counting. The originally assumed scheme, which accounted for the measurement of the number of exits and returns for two buildings erected in different periods, was abandoned. Ultimately, it was decided to choose buildings similar to each other, built in the same period of time and thus with a similar social

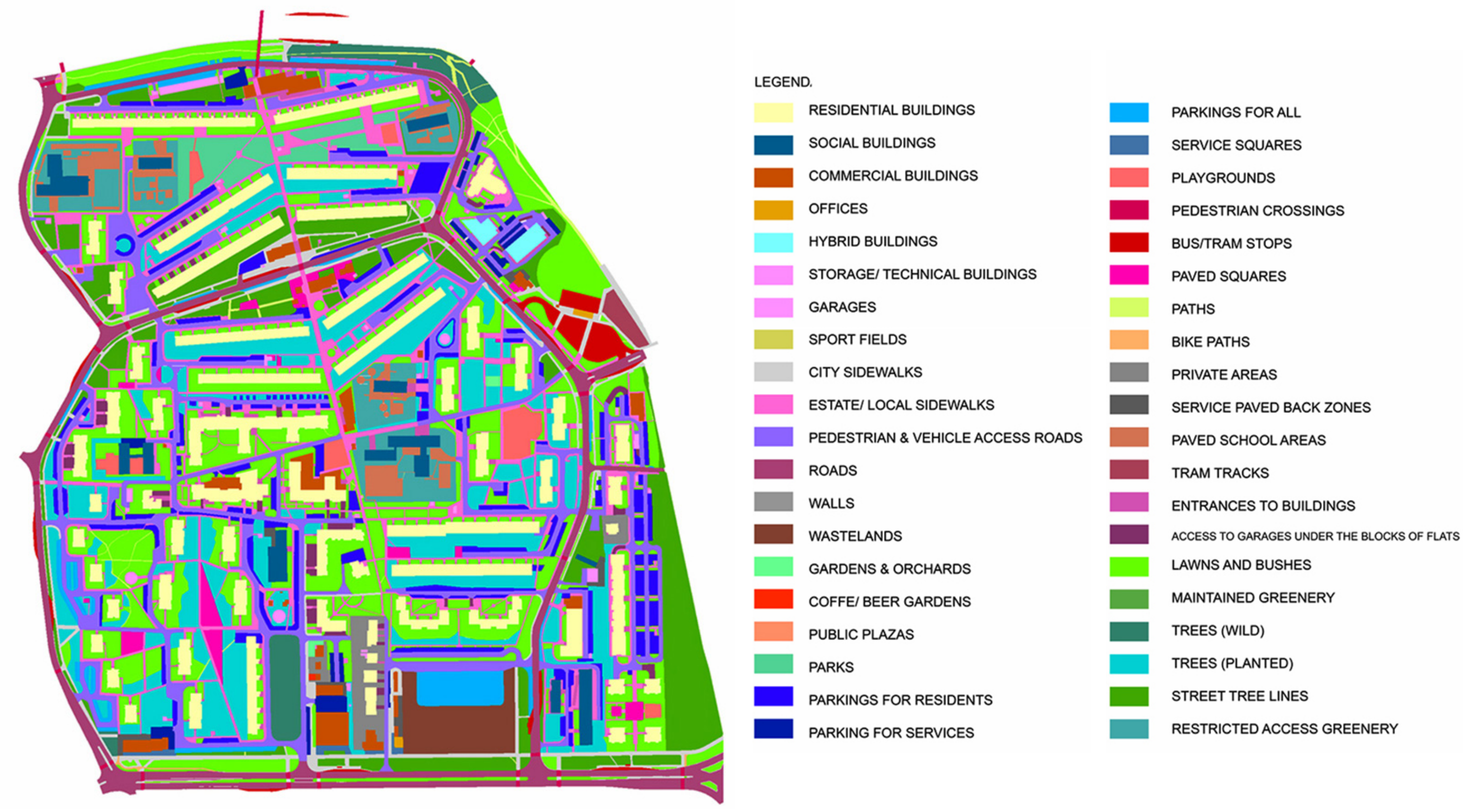


Fig. 3. Merged map consisting of 24 sections based on 40 different land uses

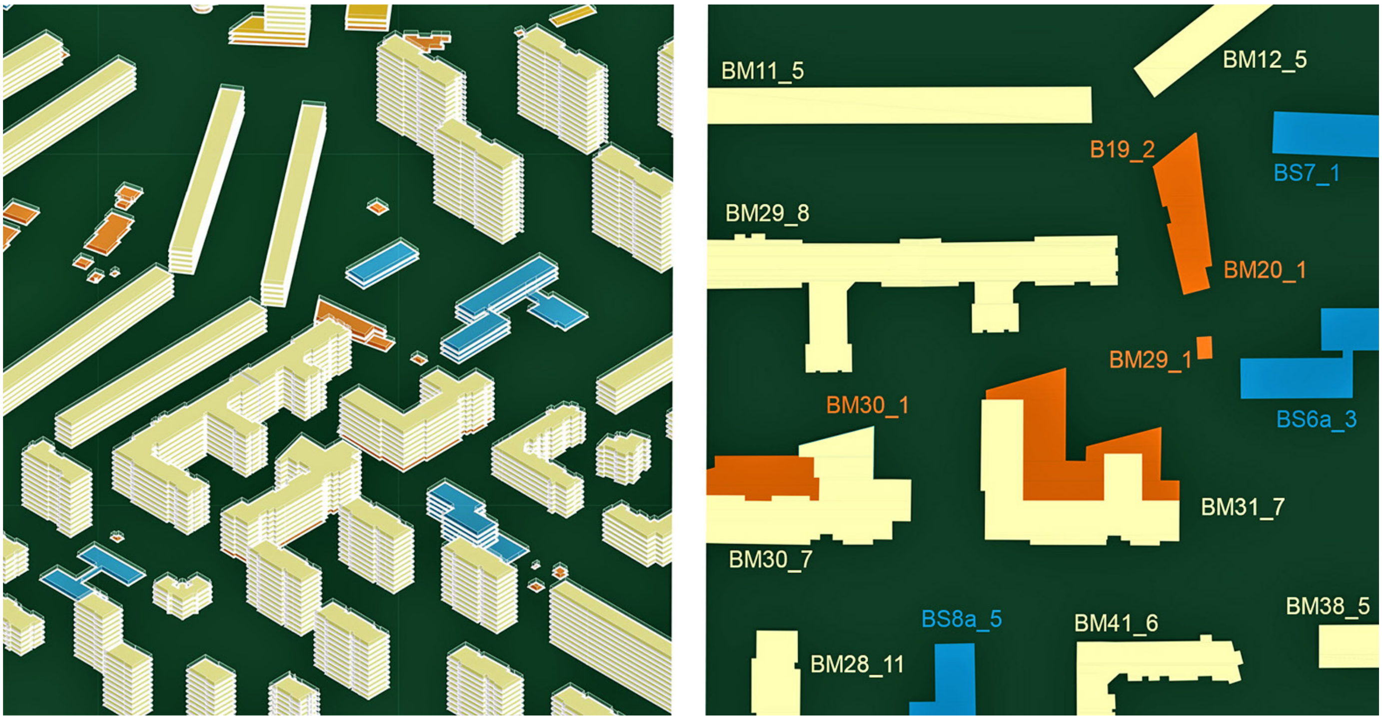


Fig. 4. Left: 3D modeling of the buildings including functional distribution. Right: building identification code

characteristics. For that reason the research results could be internally comparable. Both examined buildings were located on the main compositional axis, but at a certain distance from each other. Collective compilation of the results proved similarities, except for a few exceptions that could arise from such a limited sample of research (see Table 1).

The measurement was carried out by two students on two consecutive working days from 8 to 9 September 2020. The weather conditions were similar for the days of the study – days were sunny, the air temperature ranged from 13–16 degrees. It is important to note weather conditions as they are of particular importance as a factor in the people form of mobility choices. For that reason the obtained research results are internally consistent and the calculated numbers of people should be assigned to the days with the maximum traffic intensity due to the favorable weather conditions. The students made measurements by marking all exits and returns on a specially prepared card. In line with the recommendations of Gehl [53], whose research proved that city life is rhythmic and repeatable – one day is similar to the next, the measurement was performed for 15 minutes twice an hour for about 2 hours (4 measurements in an interval). The measurement was carried out in four time intervals of the day corresponding to the morning peak, noon hours, afternoon peak and evening hours. In this way, an image of an entire day was obtained without the need to measure continuously. The final results given in the table are an average value.

4.5. Everyday routine examination

Everyday routine examination was conducted by three students on two consecutive days on September 10 and 11, 2020. Weather showed greater variability than in the first study – from light cloudiness to sunny weather, and the air temperature ranged from 9 to 18 degrees. The lack of rainfall and the similar temperature allowed for the analyzed periods to be considered rel-

Table 1
A summary of the results of the averaged number of exits and returns

	Time	Student 1		Student 2	
		BM39		BM11	
		exits	returns	exits	returns
1	Morning peak (from 6.00 AM to 7.45 AM)	2.16%	1.04%	2.89%	0.50%
2	Noon hours (from 11.00 AM to 12.45 PM)	2.83%	0.97%	3.29%	3.39%
3	Afternoon peak (from 4.00 PM to 5.45 PM)	3.13%	3.50%	3.59%	3.09%
4	Evening hours (from 8.00 PM to 9.45 PM)	1.26%	1.93%	1.20%	2.19%

Table 2
Summary of the results of travel destinations survey for the morning peak

Building number	BM11
Estimated number of people	251
Weather condition	Cloudless, 9°C
Time period	Morning peak 6.00-8.00 AM
Date	11.09.2020

	Destination	Student 1	Student 2	Student 3	Total	Share
Transport	Car	7	3	4	14	25.00%
	Bicycle	1	1	0	2	3.57%
	Bus stop	3	7	4	14	25.00%
	Crossing for pedestrian Leading outside of the site	0	0	2	2	3.57%
Recreational activity	Playground, playing plants, parks	0	0	0	0	0.00%
	Jogging, walking with a dog	2	2	4	8	14.29%
	Visits e.g. in another building	1	1	0	2	3.57%
	Fitness clubs	0	0	0	0	0.00%
Utilitarian activity	Shopping	1	0	1	2	3.57%
	Services	0	0	0	0	0.00%
	Health – hospital, clinic, pharmacy	0	0	2	2	3.57%
	School, kindergarten, educational courses, language school, etc.	2	6	2	10	17.86%
				Total	56	100.00%

atively similar. Due to the time-consuming nature of this study, it was decided to conduct it only for just one building (building BM11). The task was to mark the places of travel destinations on the map and in the appropriate field on the research card. All activities have been assigned to 3 categories: born directly from the need for transport, recreation and utilitarian necessity. The recording was done by placing a code that contained three basic information: the following number, the sex of the examined person (F-female, M-male) and the age range (1 – school youth up to 18 years of age, 2 – people aged 18–25 years old, 3 – people 25–60 years old, 4 – people over 60 years of age (example code: 4, F, 4 means fourth person was female 60 and over years old). At this stage, information above has not been analyzed in detail, although it is a valuable source of additional data that characterizes the mobility pattern of residents. The survey was carried out at four time intervals corresponding to the morning peak, noon hours, afternoon peak and evening hours, this time continuously for two hours. At the end of the study, the results were entered by each student into the excel file, that automatically calculated the share of certain activity (see Table 2). The information on the destinations, the sex of the examined person (F-female, M-male) and the age range was obtained by means of a direct questionnaire with additional support – in case of short trips for example: walk to the car, short walk with a dog – by tracking (hidden observation). In this way, information on the residents' daily routine was obtained including both travel pattern and activities.

4.6. Data for model validation

The proposed validation method, described in Section 3.3, requires data on pedestrian traffic intensity in selected fragments of the estate and in selected periods of time. For this purpose, the entire study area was divided into two zones, in which 4 characteristic places were designated, between which two students traveled (see Fig. 5). The aim of the study was to obtain 4 comparative photos in each place with a 15-minute interval, taken in four defined time periods similar to previous tests (8.00–9.00 AM – morning peak; 11.00–12.00 AM – noon; 17.00–18.00 PM – afternoon peak, 20.00–21.00 PM – evening hours). To make this possible, it was necessary to ensure that the length of the walking loop did not exceed 1 kilometer, so that the student could start another photo series for the same locations after a quarter of an hour. Finally 128 photos were taken. The day of taking pictures, like the other days of the research, was characterized by good and warm weather. Initial validation results are described in Section 6.

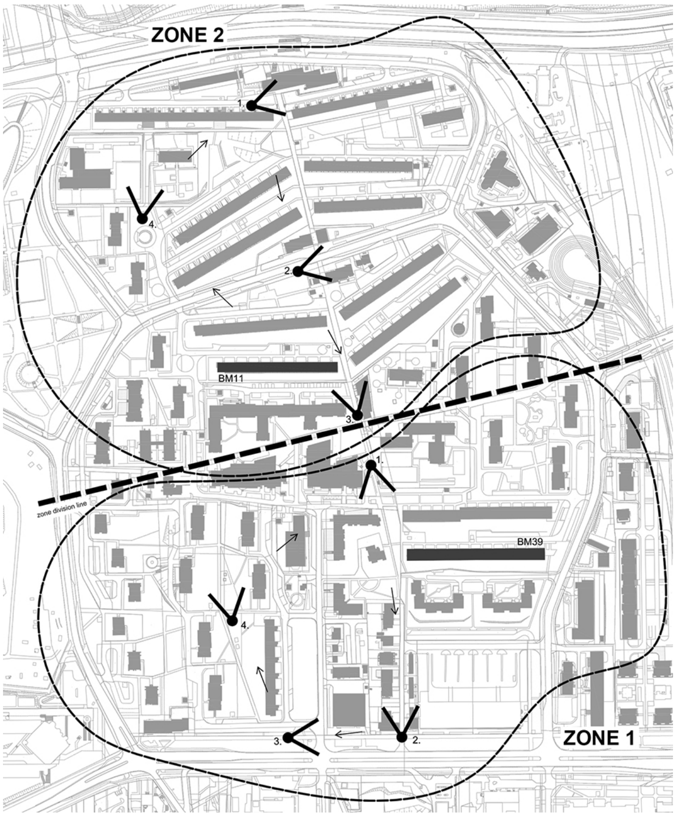


Fig. 5. Area division into zones with marking the locations of comparative photos to be taken

5. EXPERIMENTS AND RESULTS

5.1. Execution environment

The experiments were conducted on the Prometheus supercomputer which is a peta-scale (2.4 PFlops) machine located in the AGH Cyfronet computing center in Krakow, Poland. As of November 2020, Prometheus is ranked as the 324th fastest supercomputer according to the TOP 500 list. Prometheus is a cluster based on the HP Apollo 8000 nodes with Xeon E5–2680v3 CPUs working at 2.5 GHz, each node having 24 physical cores, with 55,728 computing cores total. The nodes are connected via InfiniBand FDR network.

Each simulation run was executed on 24 computational nodes, which amounts to 576 computational cores. Utilization of simulation method described in [35] allowed easy parallelization of the experiment, by dividing grid into 576 approximately equal parts uniformly distributed between computational cores.

Three variants of simulation configuration were used:

- In the baseline variant, people were not avoiding contact with each other and their creation and destinations were chosen accordingly to the distribution determined from the study.
- In the second variant, people were trying to avoid each other, while using the same distribution.
- In the final, third variant, people were trying to avoid contact as well, but additional restrictions were added to their creation: pedestrians that would be assigned strolling behavior or playground destination were not put in the grid, while visiting other residential buildings and services usage was reduced to 33% of the original frequency, i.e. 2/3 of the people that would be created with these destination types did not appear in the grid.

Each variant was executed ten times, each of the executions entailing a single day of simulated environment. A short sample from one simulation can be viewed online[3]. The results are presented in the following subsections.

5.2. Total number of registered violations

For each of the variants, the total number of social distance violations was aggregated from each run. The results are presented as the box-plot in Fig. 9. The plotted series represent different variants, as described in previous subsection, while the x-axis shows three time windows: the first is the number of the violations during the morning (6:00–8:00), the second shows the same metric during the afternoon (16:00–18:00) and the last is aggregated from the whole span of the execution. It can be easily observed, that each subsequent modification to the simulation configuration resulted in significant decrease in total cases, i.e. adding avoidance to the pedestrian behavior decreased this metric, while prohibition of certain activities—and, in result, reduction of the number of pedestrians in the area—decreased it even further. An additional observation is that the number of violations in the afternoon is more than twice bigger for the first and second variant, but for the most restricted variant the value did not change significantly. A credible explanation might be that the number of the pedestrians in the less restricted variants increased beyond the point, in which it is impossible to successfully avoid a contact, while the same increase in activity at this time of day for the last variant was still not enough to overcrowd the area.

As an important side note to the specific meaning of the numbers presented on the y-axis, a single instance of social distance violation is an occurrence of any agent representing a pedestrian occupying a cell containing a marker belonging to other pedestrian, with a distance to the source below threshold (1 m), during any iteration (1 second). As a result, most pedestrian contacts tend to generate multiple instances, as each of the participants will record separate violations, and they tend to remain in proximity for more than a single second.

5.3. Locations of violations

To further analyze the results, the specific locations of the recorded violations were aggregated in the time windows described in previous subsection. The results from single execution are shown in heatmaps presented in Fig. 6, Fig. 7 and Fig. 8. Each cell, i.e. 1×1 m area in the original map (rendered in grayscale for the clarity of the results) is assigned a color from the scale corresponding with the total number of violations in this location. Results from different variants are shown in each figure to allow comparison. To further clarify the results, locations with fewer than 5 occurrences were omitted in the figures, as such places are unlikely to pose significant health hazard.

[3] https://youtu.be/zxPy4xBU8mY

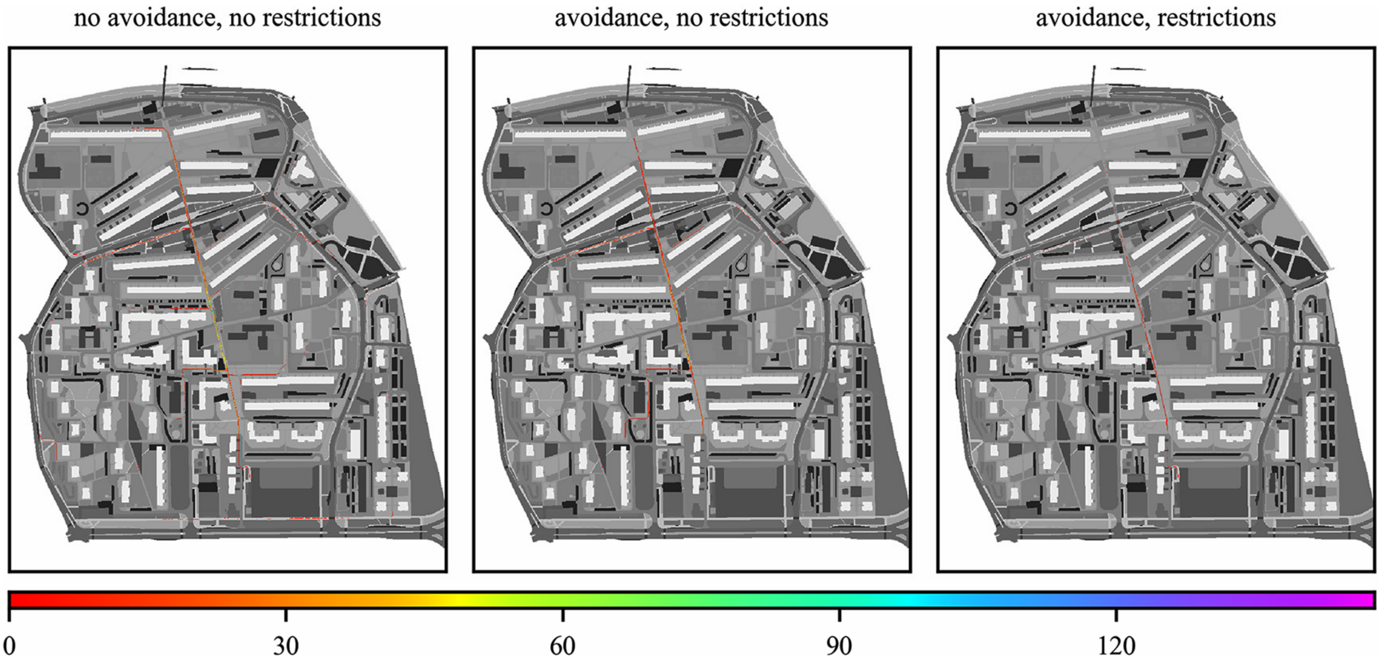


Fig. 6. Violation locations in the morning (6:00–8:00)

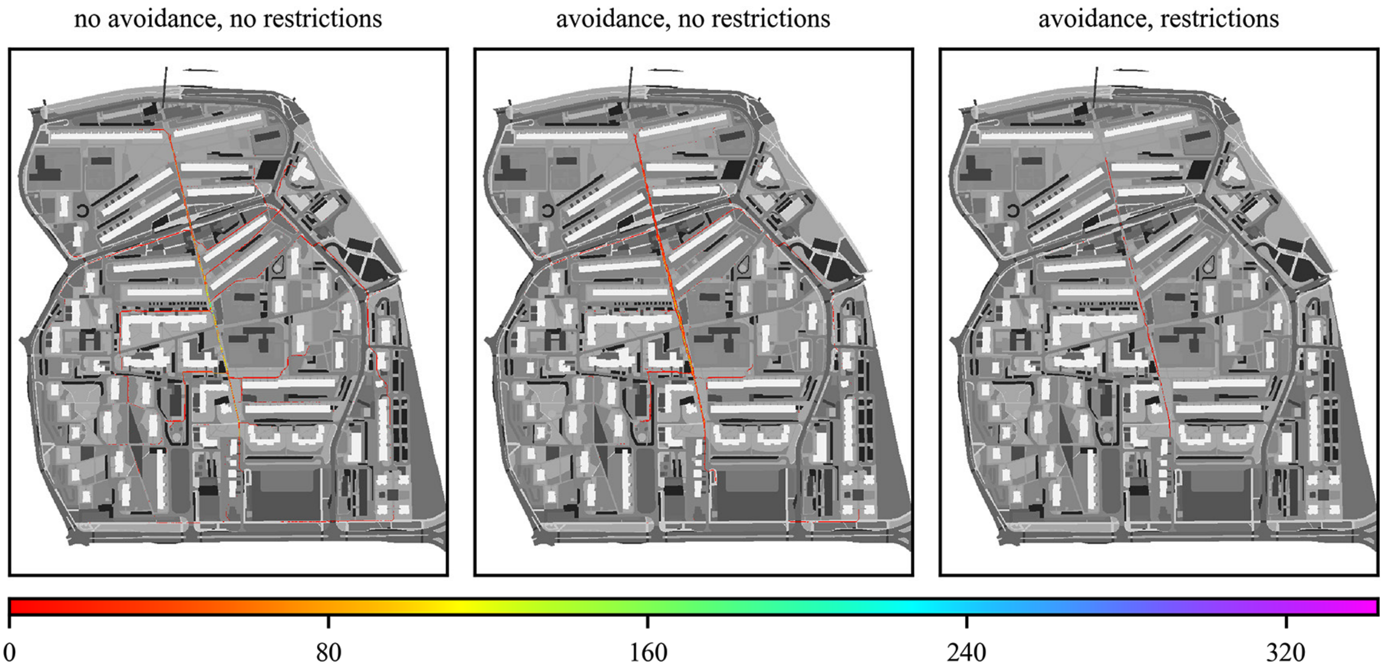


Fig. 7. Violation locations in the afternoon (16:00-18:00)

Both Fig. 6 and Fig. 7 show similar results. The variant with no modifications presents multiple sidewalks with significant number of violations, appearing mostly in the center of the sidewalk. The variant introducing the behavior of contact avoidance reduces the number of locations in which violations occur, while the central vertical sidewalk shows more dispersed locations along its length. This change might be attributed to the people willing to move to the edge of sidewalk in order to try to avoid other pedestrians, although this maneuver seems to be not enough in some cases and violation is registered despite this behavior. Finally, the introduction of the restriction in allowed activities reduced the locations of violations almost entirely to the central vertical sidewalk.

Figure 8 shows similar results to these detailed in the previous paragraph, although the aggregation of the results from the whole day is able to highlight additional areas, where the violations occur not frequently enough to appear in any partial time window.

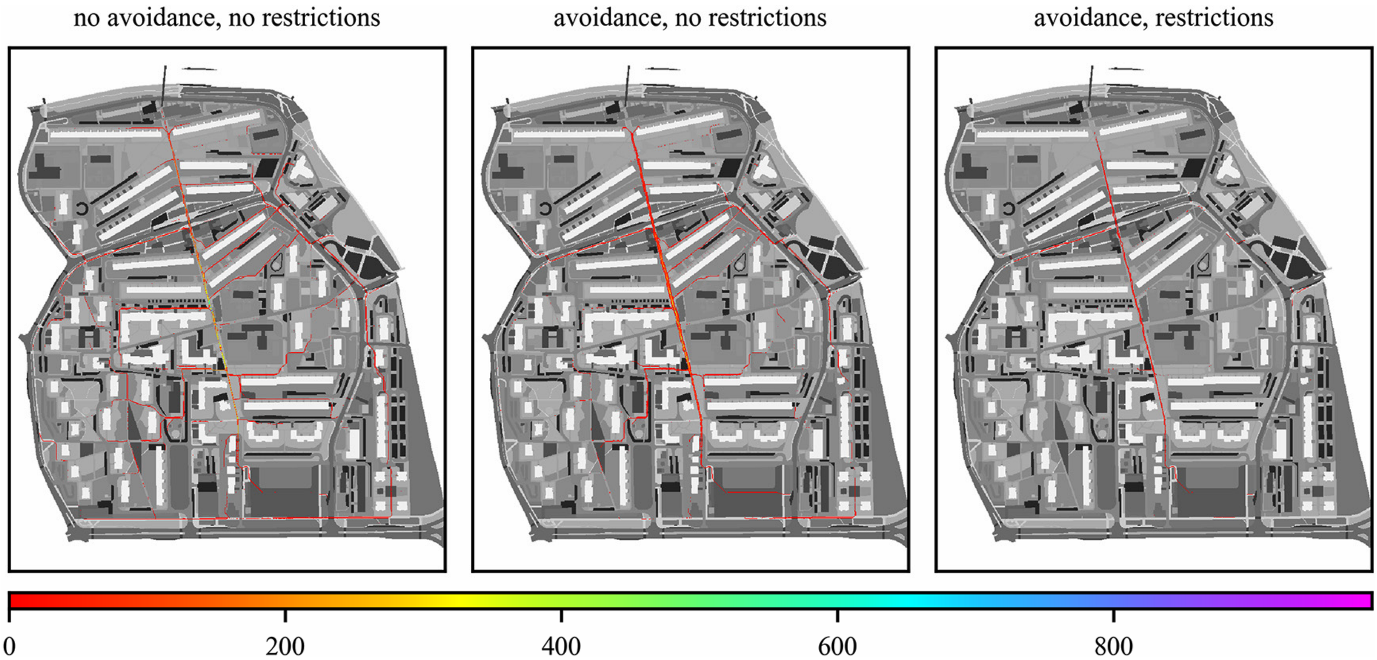


Fig. 8. Violation location during whole day

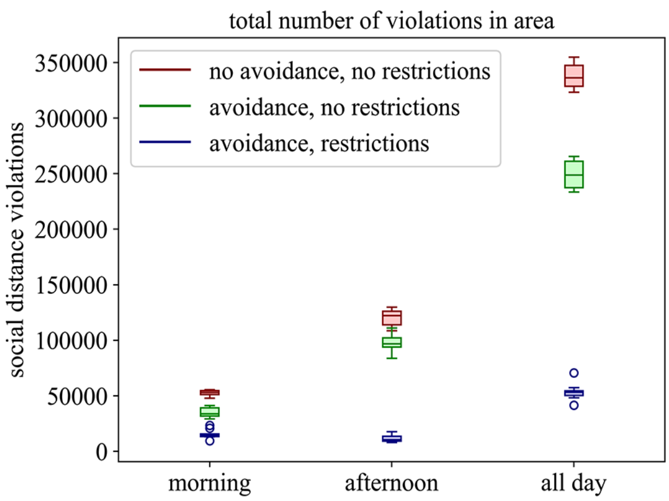


Fig. 9. Sum of all violations in the time windows: morning (6:00–8:00), afternoon (16:00–18:00), all day

6. RESULTS DISCUSSION AND ANALYSIS

For all 128 photos that were taken to verify the adopted modeling method, a comparative analysis of the number of people on the simulation frames corresponding in place and time was carried out (see Fig. 10). The analysis proved that the adopted research methodology and the traffic modeling itself show a similarity in terms of the number of people moving in the area (see Table 3). The sum of the averaged values of the number of people in the camera range for all measurement points during entire day was 104 and for the simulation 97.5. For the cumulative results in individual zones, greater discrepancies were found in zone 2 only for the morning and noon hours, which may be related to the lack of sufficient information about people moving in the study area but living outside of it. For the total number of 32 averaged measuring points constituting the measurement of the traffic distribution, about 11 of them – where greater pedestrian traffic was recorded – showed significant discrepancies.

It should also be stated that modeling of the travel destinations themselves requires more output. The percentage of the share of individual destinations is not a sufficient source of information. In the course of further research conducted

Table 3

Averaged number of people recorded in the camera frame and in the simulation in specific time intervals in all location points

Morning Peak	Zone 1		Zone 2	
	Photo	Simulation	Photo	Simulation
	8.5	7.75	12.5	5.5

Noon Hours	Zone 1		Zone 2	
	Photo	Simulation	Photo	Simulation
	14.25	12.5	16	8.75

Afternoon Peak	Zone 1		Zone 2	
	Photo	Simulation	Photo	Simulation
	19.75	24.5	19	21.25

Evening Hours	Zone 1		Zone 2	
	Photo	Simulation	Photo	Simulation
	6	9.5	8	7.75

Fig. 10. Comparative analysis of the number of people in the camera's range and in the simulation at 5.30 pm in the zone 1, location point 3

in this area, it will be necessary to develop a new, extended method of obtaining data, including the use of a sociological apparatus. People's habits and patterns of movement, specific goals, lengths of staying in a given place, frequency of visits, and the nature of the departures have not been studied sufficiently. Therefore, modeling true-to-reality traffic patterns in the area in question was more difficult. A certain explanation for the situation may be the fact that the research was conducted during an ongoing pandemic, which already had influenced the way people function [46] and, consequently, had an impact on travel behavior. How much – in this particular case – remains an unanswered question so far. Standard modeling based on the canon of the 8-hour working day is no longer applicable. Flexible working hours, remote work and, consequently, more frequent departures and returns may be the main reason for the lack of full compliance of the test results with the adopted verification method.

7. CONCLUSIONS AND FURTHER RESEARCH

The research conducted by the team brings new and significant aspects to the assessment of urban spaces in terms of the transmission of infectious diseases transmitted by airborne droplets during a pandemic period. The 'in situ' research carried out by us – in the period of moderate spread of the virus, was adopted as the basis for simulating the dynamics of possible pedestrian behavior at subsequent stages of the pandemic development, including social lockdown. The research got related to a relatively typical – compact and coherent complex of multi-family housing, with a defined group of middle-class inhabitants. The results of the analyzes may therefore translate into other similar urban and social structures of residential estates.

In spatial terms, the virtual model of pedestrian behavior is an element for further discussion on urban and architectural factors in the field of analysis and assessment of the current state. In the architectural dimension, the innovative point analysis of the dynamics of circulation allowed to distinguish particular places in the pedestrian space – such as, for example, intersecting or narrowing pavements, where distances may get violated more often. Further research got aimed at verifying and assessing 'in situ' whether architectural factors are favoring such events in these places.

The results of studies on the relationship of pedestrian traffic to the spatial structure indicate a high frequency of using the principal public axis. This axis – which is the primary element of the urban composition – meets all the principles of the correctness of urban planning. The dogma of the central public space of a housing estate with an assigned axis of activity and function in a pandemic situation, however, seems to be a drawback. It is here that the highest number of violations of social distance occurs, regardless of the adopted parameters. The otherwise socially beneficial aspects of the creation of central pedestrian systems in housing estates – in the peri-pandemic period may, as the preliminary results of our research suggest, constitute a place of danger. The outcomes of the simulations carried out so far calls into question the current approach to shaping public spaces. However, research in this area requires a further detailed examination of the urban and architectural parameters and verification of the results yielded by this work.

The validation method used in this work, while satisfying the fundamental requirements established in the process of model creation, is limited by the quantity of real-life data. If the validation in terms of distribution of measured values is to be reliable, the number of photos or other sources providing the number of pedestrians will have to increase, ideally to the point of continuous datastream, e.g. constant monitoring of selected places. These observations have to include more locations and encompass much bigger timespan to allow the construction of much more reliable statistical information on the distribution of locations of people in any given time. If such a scale of monitoring is impossible to execute, new methods of validations may have to be developed.

The results of the related research also encourage the initiation of further modeling of the urban environment – in the form of spatial modifications and transformations proposed by the team, both on the estate and architectural scale, to reduce the number of violations of the social distance. Another opportunities of further exploration of these topics are the extensions to the simulation logic, especially in the context of the modeled human behavior and additional factors influencing the spread of infection, e.g. face coverings or groups of people from single household walking together. This stage of further work simulating possible changes in the spatial situation is still ahead of us. The team intends to test the planned changes both in terms of urban planning (on a macro scale) and architecturally (on a micro-scale) on the generated dynamic model. Continuation of work is a further stage of the team's activities.

ACKNOWLEDGEMENTS

The research presented in this paper was partially supported by the funds of Polish Ministry of Science and Higher Education assigned to AGH University of Science and Technology. This research was supported in part by PLGrid Infrastructure.

REFERENCES

[1] I. Mironowicz, *Modele transformacji miast*. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej, 2016.
[2] A. Matusik, K. Racoń-Leja, M. Gyurkovich, and K. Dudzic-Gyiurkovich, "Hydrourban spatial development model for a resilient inner-city. the example of gdańsk," *Archit. City Environ.*, vol. 15, no. 43, pp. 1–2, 2020.
[3] J.L. Kriken, P. Enquist, and R. Rapaport, *City building: nine planning principles for the twenty-first century*. Princeton Architectural Press, 2011.
[4] W. Kosiński, *Paradigm of the City of the 21st Century. Between the Past of the Polis and the Future of the Metropolis*, J. Gyurkovich, Ed. Kraków: Wydaw. PK, 2016.
[5] J.F.P. Rose, *The well-tempered city: what modern science, ancient civilizations, and human nature teach us about the future of urban life*. Harper Wave, 2017.
[6] E. Rewers, *Post-Polis. Wstęp do filozofii ponowoczesnego miasta*. Kraków: Universitas, 2005, [in Polish].
[7] M. Dymnicka, *Przestrzeń publiczna, a przemiany miasta*. Warszawa: Wydawnictwo Naukowe Scholar, 2013, [in Polish].
[8] M. Gyurkovich *et al.*, *Hybrid Urban Structures*, M. Gyurkovich, Ed. Kraków: Wydaw. PK, 2016.
[9] S. Kostof, *The City Shaped.Urban Patterns and Meanings through History*. London – New York: Thames & Hudson, 1999.
[10] A.A. Kantarek, *Tkanka urbanistyczna.Wybrane zagadnienia*, J. Gyurkovich, Ed. Kraków: Wydaw. PK, 2019, [in Polish].
[11] A. Noworól, "Functional urban area as the city of the future," *Tech. Trans.*, vol. 111, no. 1-A, 2014.
[12] K. Racoń-Leja, *Miasto i wojna: wpływ II wojny światowej na przekształcenia struktury przestrzennej i współczesną kondycję urbanistyczną wybranych miast europejskich*, J. Gyurkovich, Ed. Kraków: Wydaw. PK, 2019, [in Polish].
[13] J. Teller, "Urban density and covid-19: towards an adaptive approach," *Build. Cities*, vol. 2, no. 1, pp. 150–165, 2021.
[14] C. at Johns Hopkins University, "Covid-19 dashboard by the center for systems science and engineering," 2021, [Online] Available: https://coronavirus.jhu.edu/map.html.
[15] M. Castells, "Communication, power and counter-power in the network society," *Int. J. Commun.*, vol. 1, no. 1, p. 29, 2007.
[16] R. Sennet, "How should we live? density in postpandemic cities," Domus, no. 1046, 2020, [Online]. Available: https://www.domusweb.it/en/architecture/2020/05/09/how-should-we-live-density-in-post-pandemic-cities.html.
[17] M. Kowicki, *Rozproszenie zabudowy na obszarach Małopolski, a kryzys kreatywności opracowań planistyczno-przestrzennych*. Kraków: Wydaw. PK, 2014, [in Polish].
[18] G. Korzeniak *et al.*, *Małe i średnie miasta w policentrycznym rozwoju Polski*. Kraków: Instytut Rozwoju Miast, 2014, [in Polish].
[19] GUS, "Demographic Yearbook of Poland," 2019.
[20] N.A. Salingaros, "Eight city types and their interactions: the "eight-fold" model," *Techn. Trans.*, vol. 2, pp. 5–70, 2017.
[21] J. Busquets and M. Corominas, *Cerda and the Barcelona of the future: reality versus project*. Centre de Cultura Contemporania de Barcelona, 2009.
[22] A.A. Kantarek, K. Kwiatkowski, and I. Samuels, "From rural plots to urban superblocks," Urban Morphology: journal of the International Seminar on Urban Form, vol. 22, no. 2, pp. 155–157, 2018.
[23] M. Gyurkovich and A. Sotoca, "Towards the Cracow Metropolis – a dream or a reality? A selected issues," *Tech. Trans.*, vol. 115, no. 2, pp. 5–25, 2018.
[24] P. Lorens, *Równoważenie rozwoju przestrzennego miast polskich*. Gdańsk: Wydaw. PG, 2013, [in Polish].
[25] *Back to the Sense of the City: 11th VCT International monograph book, Year 2016, July, Krakow*. Barcelona: Centre of Land Policy and Valuations (CPSV), 2016.
[26] A. Zwoliński, "Geometrical structure of public spaces in virtual city models. exploring urban morphology by hierarchy of open spaces," *Space Form*, vol. 2019, no. 37, pp. 235–243, 2019.
[27] K. Lynch, *Good city form*. MIT Press, 2001.
[28] D.C. Duives, W. Daamen, and S.P. Hoogendoorn, "State-ofthe-art crowd motion simulation models," *Transp. Res. Part C Emerging Technol.*, vol. 37, pp. 193–209, 2013.
[29] E.D. Kuligowski, "Computer evacuation models for buildings," in *SFPE Handbook of Fire Protection Engineering*. Springer, 2016, pp. 2152–2180.
[30] B. Zhan, D.N. Monekosso, P. Remagnino, S.A. Velastin, and L.-Q. Xu, "Crowd analysis: a survey," *Mach. Vision Appl.*, vol. 19, no. 5–6, pp. 345–357, 2008.
[31] K. Teknomo, Y. Takeyama, and H. Inamura, "Review on microscopic pedestrian simulation model," CoRR, vol. abs/1609.01808, 2016. [Online]. Available: http://arxiv.org/abs/1609.01808.
[32] M. Paciorek, A. Bogacz, and W. Turek, "Scalable signal-based simulation of autonomous beings in complex environments," in *Computational Science – ICCS 2020*. Cham: Springer International Publishing, 2020, pp. 144–157.
[33] J. Wąs and R. Lubaś, "Towards realistic and effective agentbased models of crowd dynamics," *Neurocomputing*, vol. 146, pp. 199–209, 2014.
[34] P. Wittek and X. Rubio-Campillo, "Scalable agent-based modelling with cloud hpc resources for social simulations," in *4th IEEE International Conference on Cloud Computing Technology and Science Proceedings*. IEEE, 2012, pp. 355–362.
[35] J. Bujas, D. Dworak, W. Turek, and A. Byrski, "Highperformance computing framework with desynchronized information propagation for large-scale simulations," *J. Comput. Sci*, vol. 32, pp. 70–86, 2019.

[36] Y. Mohamadou, A. Halidou, and P.T. Kapen, "A review of mathematical modeling, artificial intelligence and datasets used in the study, prediction and management of covid-19," *Appl. Intell*, vol. 50, no. 11, pp. 3913–3925, 2020.

[37] M. Fuentes and M. Kuperman, "Cellular automata and epidemiological models with spatial dependence," *Physica A*, vol. 267, no. 3, pp. 471–486, 1999.

[38] I. Tiwari, P. Sarin, and P. Parmananda, "Predictive modeling of disease propagation in a mobile, connected community using cellular automata," *Chaos: Interdiscip. J. Nonlinear Sci*., vol. 30, no. 8, p. 081103, 2020.

[39] M. Dascalu, M. Malita, A. Barbilian, E. Franti, and G.M. Stefan, "Enhanced cellular automata with autonomous agents for covid-19 pandemic modeling," *Rom. J. Inf. Sci. Technol*, vol. 23, pp. S15–S27, 2020.

[40] Y. Xiao, M. Yang, Z. Zhu, H. Yang, L. Zhang, and S. Ghader, "Modeling indoor-level non-pharmaceutical interventions during the covid-19 pandemic: a pedestrian dynamics-based microscopic simulation approach," *Transp. Policy*, vol. 109, pp. 12–23, 2021.

[41] T. Kapecki, "Elements of sustainable development in the context of the environmental and financial crisis and the covid-19 pandemic," *Sustainability*, vol. 12, no. 15, pp. 1–12, 2020.

[42] A. Jasiński, "Public space or safe space–remarks during the covid-19 pandemic," Tech. Trans., vol. 117, no. 1, 2020.

[43] S. Gzell, "Urban design and the sense of the city," *Tech. Trans*., vol. 113, no. 2-A, pp. 15–19, 2016.

[44] M. Hanzl, "Urban forms and green infrastructure–the implications for public health during the covid-19 pandemic," *Cities Health*, pp. 1–5, 2020, doi: 10.1080/23748834.2020.1791441.

[45] M.D. Pinheiro and N.C. Luís, "Covid-19 could leverage a sustainable built environment," *Sustainability*, vol. 12, no. 14, p. 5863, 2020.

[46] M.R. Fatmi, "Covid-19 impact on urban mobility," *J. Urban Manage*., vol. 9, no. 3, pp. 270–275, 2020.

[47] A. Porębska, P. Rizzi, S. Otsuki, and M. Shirotsuki, "Walkability and resilience: A qualitative approach to design for risk reduction," *Sustainability*, vol. 11, no. 10, p. 2878, 2019.

[48] F. Vergara Perucich, J. Correa Parra, and C. Aguirre-Nuñez, *Atlas de indicadores espaciales de vulnerabilidad ante el covid-19 en Chile*, F. Vergara, Ed. Centro Producción del Espacio, 2020.

[49] W.H. Whyte *et al*., *The social life of small urban spaces*. Conservation Foundation Washington, DC, 1980.

[50] A. Białkiewicz, B. Stelmach, and M.J. Żychowska, "Dobra kultury współczesnej. zarys problemu ochrony," *Wiadomości Konserwatorskie – J. Heritage Conserv*., no. 63, pp. 152–162, 2020, [in Polish].

[51] E. Szczerek, *Rewitalizacja osiedli wielkopłytowych a ciągłośc´ i komplementarność przestrzeni publicznej miasta*, A. Franta, Ed. Kraków: Wydaw. PK, 2018, [in Polish].

[52] B. Malinowska-Petelenz, *Sacrum in civitas: wybrane zagadnienia*, A.A. Kantarek, Ed. Kraków: Wydaw. PK, 2018, [in Polish].

[53] J. Gehl and B. Svarre, *How to study public life*. Washington, DC: Island press, 2013.