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Improving sustainable management of university buildings based on occupancy data

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ABSTRACT

The sustainability of buildings during their life cycle could be promoted by optimizing their facility management. In this sense, data-driven approaches could support the improvement of building operation and maintenance (O&M), since they can exploit collected data to provide useful correlations to assess the sustainability performance depending on the surrounding constraints. Universities are among the most relevant and large organizations, generally hosted in multi-story buildings, that could take advantage of such data to improve the sustainable goals of class occupancy and timetable. Herein, a high level of classroom occupancy is the main goal for class timetabling, while its effect on other O&M performances is generally overlooked. In the literature, class timetabling effects on universities O&M, and especially on elevators' maintenance tasks, have not yet been addressed in depth. For the first time, this work then adopts a data-driven approach to jointly optimize class scheduling and corrective maintenance actions required on elevators in university buildings. Indeed, elevators' use is strongly influenced by scheduling-dependent occupants' movement, thus being one of the main components of the total maintenance costs, and meaningly affecting safety performances. A 15 months-long experimental campaign on a university campus daily hosting up to 7000 occupants was performed to correlate occupants' presence/movement with the number of corrective actions on elevators. The data-driven correlation was then integrated with an open-source timetabling software to assess the impact of alternative timetables (affecting occupants' movement and occupancy levels) on expected maintenance needs. According to the results, the optimized timetable can reduce current elevator maintenance needs by 65%, while the classroom occupancy performance is just reduced by 7%, thus still leading to sustainable building use. The proposed optimization approach allows facility managers to implement a university class timetabling which achieves higher maintenance cost savings, thus moving towards more sustainable management of building scheduling and maintenance performances in a joint manner.

Keywords

building maintenance; building sustainability; maintenance request; elevator; timetabling; facility management

PRACTICAL APPLICATIONS

Sustainable management of university buildings should take into account the optimization of maintenance tasks, due to their impacts on time, costs, workforce, and business continuity needs. Such maintenance needs are strongly related to class occupancy and timetable, which imply users' flows and activities, especially in complex and multi-storey buildings. Elevators are strongly influenced by scheduling-dependent occupants movement, thus being one of the main components of the total maintenance costs, and meaningly affecting safety performances. Data-driven approaches can reduce uncertainties on unpredictable faults depending on scheduling. Data collected by Computer Maintenance Management Systems on end-users' requests can thus be used to provide correlations between occupancy and maintenance needs, in view of their implementation in Building Automation and Performance Systems. Such correlations can (a) support facility managers in predicting critical conditions implying corrective actions, (b) inform decision-makers on how to better define facility management contracts, since they can estimate additional efforts based on building use, and thus (c) improve the maintenance sustainability by allowing decision-makers adopting optimized classes occupancy (when correlations are implemented, for instance, in simulation tools). The proposed approach to timetable optimization could be also extended to other scheduling-based activities (e.g. offices, congress and cultural centres, large medical offices, recreative buildings, other administrative buildings open to the public, mixed-use buildings, and ideally, large and long-term construction sites), and systems or components with which users can deeply interact depending on scheduled tasks (e.g. lighting systems, ductless air conditioning devices, safety handles, pavings).

2. INTRODUCTION

The optimization of operation and maintenance (O&M) tasks during the building life cycle can significantly improve the sustainability of buildings, and should be based on a joint understanding of the interactions between the different building components, systems, management procedures, facility managers, technical staff and users acting within the built environment (Almeida et al. 2020; Bortolini and Forcada 2020; Chiang et al. 2016; Gilani et al. 2022; Gunay et al. 2019; Jafari et al. 2019). Regardless of the specific context (e.g. modern versus historical buildings), such sustainability issues should encompass several impacts, mainly relating to (Bortolini and Forcada 2020; Cruz Rios et al. 2021; Li et al. 2021; Maslesa and Jensen 2019; Massafra et al. 2022; Peng et al. 2020; Stazi et al. 2017): (1) environmental issues, which are widely connected to building operation (e.g. energy consumptions) as well as on circular economy concepts, in view of reuse and adaptation of buildings and their components; (2) economic issues, since O&M costs can reach up to 75% of the initial construction costs; (3) whole management tasks, since faults or inadequate operation conditions, and related maintenance needs and activities, can compromise the building business continuity; (4) occupant safety, health, comfort, productivity, and, from a general standpoint, satisfaction, which are generally connected with all the aforementioned management issues, in view of the paramount role of end-users in affecting the building status over the time.

In this wider picture, large, multi-storey public buildings are relevant scenarios since they are characterized by a significant number of hosted users, who interact with the building components, equipment, layouts, and construction technologies (Almeida et al. 2020; Gunay et al. 2019; Stazi et al. 2017). Utilities, supplies, their operation and related maintenance interventions on building components and equipment are then strictly related to the presence and movement of the occupants, and not only to the features of the buildings themselves. Occupancy scheduling and activities timetabling are hence paramount factors affecting O&M needs (Lindahl et al. 2019; Ward et al. 2019).

Universities are exemplary buildings in this context, considering the different scheduled activities and daily high number of occupants, affecting both operation (e.g. energy uses) and maintenance performance, impact and costs (D’Orazio et al. 2022; Lindahl et al. 2018; Mokhtari and Jahangir 2021; Palis and Saidin Misnan 2018; Razali et al. 2020; Sun et al. 2021). Technical systems, such as elevators and mechanical stairs, are necessary to ensure the movement between different floors, depending on classes timetable and activities schedules (Vermuyten et al. 2016), and so their continuous use strongly impacts O&M performances, especially for universities hosted in large multi-storey buildings (Lang et al. 2016; Li et al. 2014; Niu et al. 2021; Olander and Eves 2011; Zubair and Zhang 2020). For instance, considering operation tasks, the continuous use of elevators implies high energy use, which can reach 25%-40% of the total energy consumption in a building

(Tukia et al. 2016; Zubair and Zhang 2020). At the same time, elevators are critical building systems, requiring frequent, and often very expensive, maintenance interventions, also considering safety reasons (Dzulkifli et al. 2021; Niu et al. 2021).

While previous works tried to evaluate how university management could affect operation needs thanks to data-driven approaches, maintenance issues seem to be limitedly investigated (D'Orazio et al. 2022; Gunay et al. 2019; Hong et al. 2022; Ma et al. 2020; Song et al. 2017). In a general way, sustainable maintenance activities should first balance planned interventions as the best ways to avoid business continuity interruptions and ensure adequate user satisfaction (Dzulkifli et al. 2021; Ibbs and Terveer 1984; Ma et al. 2021). Such actions are generally included in facility management contracts, which have been introduced in O&M in view of the complexities of current building technologies, systems and uses (D'Orazio et al. 2022; Sourav Das Adhikari et al. 2019). Nevertheless, unpredictable faults could still occur, including when variations in the building use can occur, also in view of the building schedule. The required time and efforts to supply related corrective maintenance actions could imply relevant needs for the facility managers and the contractors, mainly in terms of economic and workforce sustainability and one of the fundamental topics in this sense is the needed improvement of the coherence between the services delivered by the facility management contractors and the "demand organization" needs (Dzulkifli et al. 2021). A set of other preventive maintenance actions could be combined with planned activities to reduce the impact of corrective needs. The building use conditions, also in terms of scheduling and users' behaviours, could be then compared to their effects on components and equipment faults and problems, according to a predictive (or even a "condition-based") perspective in building maintenance (D'Orazio et al. 2022; Gunay et al. 2019).

The tools used by corporate facility management, exploiting building digitalization, i.e. databases (e.g. those relating to Computerized Maintenance Management Systems - CMMS), could actively support these steps (Johannes et al. 2021). In fact, they can collect inputs to support data-driven maintenance planning which can contribute to informed, optimized and, thus, more sustainable strategies for building maintenance (Ma et al. 2020). Faults on building systems and components, including elevators, are generally collected by the building managers mainly thanks to occupants' reports (e.g. text messages, e-mails), commonly called "work orders" (WOs) (Bortolini and Forcada 2020; D'Orazio et al. 2022).

Faults reported in WOs can be detected during occupant permanence in the building and hence correlated with activities scheduling, thus also being a benchmark for building maintenance performance (Dutta et al. 2021; Marocco and Garofolo 2021). Given the aforementioned context of universities, these data could be ideally used to improve the sustainability of class occupancy and timetable. Nevertheless, the majority of current approaches to create university class timetables usually includes only didactic constraints, to avoid lessons overlapping, to ensure the highest occupancy of classrooms (this is usually the main Key Performance Indicator (KPIs) (Vermuyten et al. 2016)), and to reduce perturbations (Lindahl et al. 2019). Several algorithms were proposed to optimize university class timetables (Gülcü and Akkan 2020; Song et al. 2018), but efforts to introduce other types of constraints were limitedly performed, mainly focusing on energy-saving goals (Song et al. 2017; Sun et al. 2021), or to solve overcrowding problems (Vermuyten et al. 2016). In this context, to the authors' knowledge, class timetabling effects on building O&M, and especially on elevators' maintenance tasks, have not yet been addressed in depth.

In view of the above, this work adopts a data-driven approach to jointly optimize class scheduling and corrective maintenance actions required on elevators in university buildings. The combined performance optimization is founded on the development of a correlation model between occupants' movement with the number of elevators' maintenance actions. A 15 months-long campaign on a university campus is performed to this end by taking advantage of: (1) a survey on students' presence and preferences concerning the use of elevators, and (2) the collection of WOs on elevator faults by end-users. Then, correlations are integrated with opensource timetabling software (Fahmy et al. 2014), based on genetic algorithms, to jointly check the impact of alternative timetables on two key performance indicators: (1) the expected number of maintenance requests, which should be ideally minimized; and (2) the occupancy level, which assesses the management sustainability and reliability of the timetables. Such alternative timetables consider different resulting student movement scenarios in view of alternative classroom use rules, thus moving towards sustainability improvement in the maintenance context.

2. PHASES AND METHODS

2.1. Phases

Figure 1 shows the general methodological framework applied to the case-study, the Engineering Faculty of Università Politecnica delle Marche (Ancona, Italy – introduced in Section 2.1.1), based on the following three steps, further detailed in the next sections:

1. the expected elevators' use by students was assessed by collecting and analyzing data from: (a) technical drawings and datasheets about the building layout, components and systems, as well as elevators' technical features and use; (b) timetables and questionnaires to students, which provided information on the mean number of students daily attending classes and their habits in terms of elevator use. This task has been completed at the beginning of the research, thus between January 2018 and March 2018. Methods are detailed in Section 2.2.1;
2. collection and analysis of data on elevators' WOs were performed, to derive the number of WO for each elevator and users' perceptions. This task started in January 2018 and ended in March 2019, thus consisting of a 15 months-long monitoring period. Methods are detailed in Section 2.2.2;
3. experimental-based correlations between maintenance WOs and elevators' use were derived and implemented as additional constraints in a class timetabling software. Four scenarios were then compared, characterized by different constraints about admissible students' movements between classrooms. Maintenance performance (in terms of WOs number) and classrooms use (in terms of occupancy criteria) were adopted as KPIs to evaluate the effects of constraints due to such four scenarios. An overview of economic issues was also performed. This task has been completed after the monitoring period. Methods are detailed in Section 2.2.3.

2.1.1. The university campus case-study

The main campus of Università Politecnica delle Marche, located in Ancona (Italy), hosts the Faculties of Engineering, Science and Agriculture and is composed of several multi-story buildings (total gross floor area of about 67000 m^2). The current study focused on the Engineering Faculty buildings (Figure 2). Buildings block A hosts 41 classrooms, laboratories, offices, libraries, study rooms and services, which are arranged into ten buildings (identified by colours and codes in Figure 2), nine of them physically interconnected in a large multi-storey complex. Given the ground slope, buildings are displaced on twelve floors, but classrooms are arranged on five levels. Buildings block B, named BAS and hosting classrooms and services, has 3 levels and its 7 classrooms are arranged on 2 floors. All the buildings have an inter-floor height of 5m.

The Engineering Faculty hosts 7 degrees and 8 master-degree courses, giving rise to about 450 different classes for a year. The students' presences have a cyclic trend in view of the organization of Faculty didactic activities, which entail: A) two-class cycles (October-December; March-May), during which the weekly class timetable is repeated for about 13 weeks, involving the same mean number of attending students; and B) two exams periods (June-August; January-February) when the students' number depends on daily exams for each course. The students' number is higher in class cycle periods than in exams period. The enrolled students are about 7000, and about 4500 daily attend classes and activities. Lessons are arranged into 1-hour-based time slots, starting at 8.30 and ending at 18.30, from Monday to Friday (lunch break: 12.30 to 14.30). A 15 minutes-delay in starting a class after the previous one is adopted.

Supplementary material S1 provides the plans of building blocks A and B, identifying classrooms, paths network between classrooms and to the elevators/staircases, and buildings entrances.

Table 1 provides information on the 15 elevators operating in the buildings in terms of: elevator identification code; the building where it is placed; the total number of served floors; the number of floors hosting classrooms; additional comments on the elevator features and use. Buildings block A includes 13 elevators (A1 to A13) and BAS entails 2 elevators (A1M, A2M). All the elevators have the same speed (about 1 m/s) and a maximum car capacity of 11 people, except A3 (5 people). The elevators are regularly maintained. In the whole campus, the median number of floors served by the elevators, and serving classrooms, is equal to 3.5 (mode 4), according to not normal data in Table 1. Floors with classrooms are generally placed between the ground floor and the 4th floor, even if the buildings may have more floors.

Table 1 also provides notes on elevators' use by students during the monitoring period (section 2.2.1). Students declared a very limited use of A1M and A2M, because of their distance from the main entrance, and of A13, connecting classrooms and a secondary exit. A1 and A2 allow the connection of each floor of the principal building in building-block A and are hence subject to the greatest workload considering the use of classrooms. A4, A5 and A12 are internal to departments, not used by students, and therefore undergo limited workloads. A11 was not working during the monitoring periods due to construction works in the area.

2.2. Methods

2.2.1. Data collection and analysis on building layout, occupants' movements and elevators' use

At the beginning of the research (January 2018), entrances, corridors, classrooms, elevators, and staircases used by students were identified by the technical drawings of the University technical office. Each classroom was classified in terms of position and number of seats. Each elevator was characterized by: capacity (maximum number of people hosted in the car); mean speed (m/s); run length (vertical distance between departure and arrival floors, in m). Staircases that can be alternatively used by students were characterized by the same corresponding vertical distance. No variations to these elements occurred during the research.

The main indicator for elevator use assumed is the potential *Daily Elevator Use* (DEU), which expresses the distance covered daily by runs of each elevator (m). Figure 3 resumes the DEU calculation according to these variables and the related adopted methods. The DEU essentially depends on the occupants' movement and on the elevator features (Olander and Eves 2011) and thus, in detail, on: the adopted timetable and the number of students attending daily lessons (step 1 in Figure 3); the analysis of students' movement depending on the path configuration (which is hence based on the layout of the building (step 2 in Figure 3), on the elevator car capacity and run length (step 3 in Figure 3); and on the students' declared preferences regarding the use of stairs and elevators (step 4 in Figure 3).

Concerning step 1 in Figure 3, data about the class number for each course, course duration during the academic year, number of students per class, and class timing (daily and weekly) were first organized. The number of students attending courses was based on: (a) the number of seats in the classrooms, depending on the timetable; (b) the number of effectively enrolled students for each class in two consecutive academic years before the Covid-19 pandemic (2018 and 2019). Moreover, for each classroom, the Occupancy Ratio (OR) was calculated as the ratio between the total occupied hours (by classes) and the maximum number of available hours in the classroom. OR represents the occupancy level (in a range of 0-100%) and should be maximized.

Then, the analysis of students' movement between classrooms was carried out according to the following movement assumptions and by organizing the paths network organized in the open-source software Peklo (https://sourceforge.vnet/projects/peklo/) (Figure 4). The assumptions about students' movements concern the path selection and the movement timing to complete steps 2, 3 and 4 in Figure 3.

The path selection criteria (step 2 in Figure 3) considers students while moving from the starting point A to the arrival point B. Figure 4A shows a schematized example of this task, considering that A and B are two classrooms (but the same concept can be extended for students' movement from or towards a building entrance. Each student, moving from A to B, selects the shortest path, that is the one with the minimum geometrical length (in meters) between the possible selectable ones (Lang et al. 2016) thus using a "static" minimum-cost flow problem. In detail, the length of the path was calculated as the sum of corridor lengths and vertical distances (staircase, elevators). The shortest path is marked in green colour in Figure 4A, while the alternative one is marked in red and it was not considered in the rest of the students' movement analysis. The movement timing depends on these paths and on the elevators' capacity (step 3 in Figure 3). The calculation was based on the assumption that all the students moved at the same time, without significant flow reduction both along stairs and corridors as the maximum density is up to about 2.5 pp/m^2 (Banerjee et al. 2018). Students' speed has been assumed equal to 1 m/s (Bosina and Weidmann 2017). Furthermore, the movement timing was then affected by the elevators' overload, which depends on the maximum car capacity (Table 1). According to a conservative approach to elevator use, when the car is full, students, who choose to use the elevator, spend time waiting for the free car. As a result, the students' overall travel time is the sum of the walking time, the eventual waiting time for a free car, and the elevator travel time. The total time should be ≤ 15 minutes, that is the time lag between two classes. In this work, the elevator call button is pushed before the elevator run, thus each calling and the related use contemporarily contributes to the increment of the run length and to the users' transportation between two floors. The students who cannot use the elevator because the travel time is > 15 minutes are assumed to directly use the stairs. The maximum walking distance in 15 minutes is 900m, which is significantly higher than the length of the effective paths (the maximum path is about 250m long). To verify the timing assumption, in-situ verifications were carried out during a survey, confirming no overcrowding conditions and that the maximum movement time between two classrooms was smaller than the time lag between two classes, also in the case of people waiting for the use of free elevators.

Following these assumptions, and due to the complexity of multiple paths connecting two classrooms, the network of the paths was organized through Peklo, as shown in the excerpt of Figure 4. Peklo is a graph editor which allows graphically creating and visualizing complex graphs (defining arches and nodes and, if needed, their weights), and also comparing different algorithms for solving graph-theoretic problems, including shortest path assessment. In the Peklo network shown in Figure 4B, classrooms (black dots), elevators (green dots) and staircases (red dots) were considered nodes in the overall path network (identified by numeric codes), and thus linked by connection lines.

Finally, the elevators' use by students depending on their preferences (step 4 in Figure 3) was assessed by questionnaires administered to a significant occupants' sample (about 10% of students daily attending the campus, i.e. 433 questionnaires), for two weeks and at different hours of the day, in March 2018, during the lesson periods (so at the maximum building capacity). Each student was asked to define his/her path followed at that moment, by considering: a) attended a course and usual frequency at classes during the day/week; b) departure and destination places; c) reasons for displacing (i.e. attending classes, reaching other facilities as library or coffee, reaching study rooms); d) if staircases and/or elevators were used during their journeys, and the number of travelled floors; e) if he/she usually used that path to move from departure to destination places. Questionnaire results allowed defining the percentage of students who choose to use the elevator while reaching another classroom, depending on the number of travelled floors.

As the final output (Figure 3), the length of each elevator ride (m) at each class change was calculated for each elevator, and then the DEU was estimated as the sum of these lengths over the day, by considering the aforementioned elevator capacity and speed, and the tolerated delay to attend a class (15 minutes). The DEU was calculated in reference to three scenarios in terms of students' usage:

- *critical:* the total number of students is defined by the number of seats. DEU corresponds to the maximum load on elevators due to the maximum number of possible occupants;
- *nominal:* the students' number is equal to the number of students enrolled in each course. DEU corresponds to the maximum load on the elevators caused by the enrolled number of students (less than in the critical scenario);

- *effective:* the students' number is equal to the percentage of questionnaires-based presences. DEU is scaled by the mean percentage of students that declared to prefer the use of elevators instead of stairs (less than in the critical and effective scenarios).

2W-DEU (m) was defined as *DEU* for the number of days with lessons in two weeks, to compare results obtained in the questionnaires campaign period. *DEU* and 2W-*DEU* were also normalized by the number of served floors to directly compare data on different elevators based on the same floors' configuration.

2.2.2. Data collection and analysis on maintenance work orders

Università Politecnica delle Marche externalizes facility management activities. The external contractor (ANTAS s.r.l.) grants the full functionality of all plants and building components, managing all O&M activities. End-users' maintenance requests following faults events are collected and managed continuously, translated into Work Orders (WOs) and finally interventions are performed. Hence a database of WOs due to faults in the building components and equipment is available. The database includes the end-user's maintenance request, the technical category (i.e elevator, fire, etc…), and the date of the intervention. Figure 5 shows the WOs production and management flow.

Since each WO begins with reporting of anomalies or faults by non-technician personnel (e.g. student, teacher, staff members), WOs data consist both of numerical and unstructured textual data (via e-mail) including personal perceptions, thus requiring both data and text mining analysis tools (Bortolini and Forcada 2020; D'Orazio et al. 2022). The WO analysis was carried out for an overall monitoring period of 15 months (from January 2018 to March 2019), in collaboration with the facility management contractor of the University, to derive the mean number of weekly faults for each of the 15 elevators of the Engineering faculty. 2166 WOs were collected during this period, and 101 WOs were due to elevator faults (4.6%).

Numerical data were processed through the statistics language "R" rel. 4.0 (Williams 2011). Textual data (in the Italian language) were analyzed through "R" rel. 4.0, by using the Text Mining TM (https://cran.r-project.org/package=tm) and Quanteda (https://cran.r-project.org/package=quanteda) packages. These packages allow automatic analysis of users' requests to detect the frequency of relevant terms within the textual data (e.g. types and causes of faults; elevator components involved; position of the elevator and its identification within the buildings). The use of text mining techniques avoids long-lasting and timing consuming tasks on manual analysis of WOs, which can be composed of many sentences and phrases. Moreover, text mining can be employed in larger datasets according to the adopted data-driven approach (Bortolini and Forcada 2020; D'Orazio et al. 2022).

2.2.3. Correlation analysis between occupants' movement and elevators' maintenance, and impact assessment on classes timetable

Correlation analysis has been performed on the students' movement data and the number of elevators' faults. In particular, an algorithm to estimate the expected elevator two-week WOs depending on the 2W-DEU (m) was developed, using data on the class timetable and considering the different occupancy scenarios. The two weeks-scaling was used to obtain a consistent WOs number in the questionnaire period.

The algorithm adopts a regression model based on the logistic function, which is an S-shaped model. This is widely adopted by models representing the interaction between human behaviours and building systems, including elevators (Li et al. 2014; Stazi et al. 2017). In our application, it represents growth processes depending on three main assumptions. The lower limit considers no WOs because the elevator is not used. WOs number grows when elevator use increases, but a non-linear trend can be assumed according to the aforementioned studies. The upper limit is a physical limit since elevator overloads can imply a maximum travelled path length per day depending on the elevator speed and capacity. According to Section 2.2.2, this logic also relies on the fact that the button is pushed before the elevator run, thus each elevator travel implies that the *DEU* increases since users are can move to another floor. This conservative assumption is adopted to stress the users' interactions with the elevators since it was not possible to carry out an experimental campaign to detect the number of callings without elevators' use. Elevators not or limitedly used by students were excluded from the fitting process. The reliability of the logistic function-based algorithm has been tested by using "Curve data fitting" module of Matlab R2019b and applying the "nonlinear least squares" method.

Finally, the algorithm was applied in combination with the timetabling opensource software FET (ver.5.48, https://lalescu.ro/liviu/fet/), used by several high schools and universities (Fahmy et al. 2014). FET adopt genetic algorithms to find the optimal solution, releasing progressively adopted constraints. FET considers space and time constraints, due to teachers, classes, activities, and buildings, in order to: (1) allocate the occupants in the classrooms avoiding overlapping and holes in the timetable; and (2) reach the highest occupation level of the classrooms.

For each semester, a list of teachers (231), subjects (413), classes (53), classrooms (41) and available devices in each classroom has been realized. Then, specific constraints between teachers, subjects, and classes, were introduced to create the initial dataset. Spatial constraints related to students' movement in each scenario were defined by associating groups of students only to a specific group of classrooms. In addition, typical space and time constraints were maintained, i.e.: the number of classroom seats must be greater than the related students' group dimension; no lesson overlapping for students and teachers; break for lunch; a maximum number of days intercurrent between the same course class).

In addition to these constraints, an additional one was considered, related to students' movement between classrooms, thus originating four alternative scenarios:

- *Scenario A*: keeping students inside classrooms located on the same floor level;
- *Scenario B*: keeping students inside classrooms located within the same campus building;
- *Scenario C*: keeping students within two specific building-blocks (buildings-blocks A and B);
- *Scenario D*: equal to Scenario C, with an additional limitation on students' movements between the floors.

Scenario C is quite similar to the timetable in use during the academic year 2018/19, thus it was assumed as the reference scenario.

The building performances in the four alternative timetable scenarios were compared in terms of the following KPIs: (1) expected WOs, depending on 2W-DEU, to assess maintenance issues; and (2) OR for the whole campus, to assess the timetable sustainability regarding the hosted activities. The best timetables should combine low expected WOs while maintaining a similar OR to the current situation (i.e. the reference Scenario C). Finally, an overview of economic needs in significant scenarios has been performed by considering the current standard expenditures of the building owner for elevator WOs, based on historical data.

3. RESULTS

3.1. Current use of the buildings in terms of classrooms occupancy and elevators load

The classroom dimension at the Engineering Faculty varies from 35 to 344 seats (median: 93). Outliers are given by the biggest classrooms hosting more than 200 seats (Figure 6).

Figure 7 shows the distribution of the students' groups dimension for the 443 different classes delivered in the academic year 2018/19. As expected, the students' group distribution fits with the classroom distribution, also considering that larger students' groups were subdivided into two sub-groups, hosted in different classrooms at the same time. Figure 8 shows the classrooms OR distribution in terms of the probability density function. The OR values range from 40% to 90% (median: 68%; mode: 72%).

Figure 9 resumes the main results from the 433 questionnaires on the use of stairs (light grey) and elevators (black), depending on the vertical distance between starting and arrival floors (moving downstairs or upstairs). Students generally preferred to use the stairs, but the percentage of occupants using the elevators increases with the increase of the number of travelled floors, especially while moving upstairs (i.e. 20% for two floors, that is 10m; 30% for three floors, that is 15m). In addition, students generally used elevators to move between floors to attend lessons (61%), reach other facilities (10%), or reach study rooms during time breaks (29%).

Finally, students usually follow the same path, so certain elevators are burdened, i.e. A1 and A2 because of the high number of interconnected floors (maximum expected load), and A3 and A10 because of the high number of nearby classrooms.

Table 2 shows the elevators use scenarios, expressed as *2W-DEU* and normalized *2W-DEU* (by the served floors number), depending on "critical", "nominal" and "effective" classroom occupancy scenarios (defined in section 2.2.1). Table 2 excludes the elevators according to Table 1 assumptions.

3.2. Data and text analysis of maintenance work orders

Figure 10 shows the monthly distribution of WOs concerning elevators during the monitoring period. WOs peaks correspond to starting months of classes (March, October) and other activities after holidays (January, September). Table 2 also reports the WOs number for the elevators, which increases with the assumed elevator use.

The textual analysis of e-mails on elevators WOs are performed by considering only words mentioned more than 10 times. Results show that more than the 40% of terms only referred to general data such as the general type of faults (“blocked”, “stopped”), the “elevator” identification “code” or the place and ”floor” where the fault happened. This kind of outcome can be essentially due to the fact that communications are sent by non-specialised users. In fact, “elevators” is the most common word, having a frequency equal to 11%. A lower frequency, between 1% and 9% relates to general words such as “blocked”, “floor”, “stopped”, “doors”, “cabin”, “fault”, or to the identification “code” of the elevator. On the contrary, details on the type of damage or the elevator part (“cabin”, “car”) involved in the fault are more limitedly provided, using not exhaustive information. In these cases, such kind of details is mixed with personal perceptions (e.g. “it seems that…”, “my impression is…”). The most cited elevators (2% to 4%) are A1, A2 and A3, as expected (compare to Table 2), since they are the most used.

3.3. Correlation between occupants’ presence and movement and maintenance work orders

Data on 2W-*DEU* (m) were correlated with the WOs number during the same monitoring time period for the elevators included in Table 2. 2W-DEU refers to the “effective” normalised occupancy scenario in terms of presences (Effective_N, in Table 2) which allows: A) reproducing the most realistic conditions in terms of the number of students and elevator use preferences, according to the “effective” scenario; and B) comparing data of each elevator according to ideal equality in floors configuration, thanks to the normalization procedure.

Considering that a WO of a specific day is not related to the elevator use during the same day but to the use during the previous weeks, we analysed data in an aggregated form, that is the total WOs produced during the monitored 15 months and the elevator rides in the same period.

Equation 1 shows the correlation according to the logistic regression model, which general rules are described in Section 2.2.3.

$$y = \frac{(k-a)}{(c+q*e^{-b*x})} \quad [1]$$

In Equation 1, *x* is two-week WOs (-) and y is the 2W-DEU (m) according to Effective_N in Table 2. The pairs used for the regression model assessment are the experimental ones. The model is hence characterized by:

A) the lower limit, which corresponds to non-maintenance requests in case the elevator is not used by occupants; and B) the upper limit, that is due to the maximum 2W-DEU of each elevator depending on its speed. a, b, c, k, and q are typical regression model constraints based on the fitting process and they can express the shaping of the regression model depending on the experimental pairs. Results for the whole x-y input pairs (mean model) show the following fitting statistics: SSE: 4.136e+06; R-square: 0.90; Adjusted R-square: 0.80; RMSE: 491.5. Fit uncertainties are mainly related to the starting point of the curve slope associated with the adopted logistic function. Thus, we derived maximum and minimum regression models on the data envelope, alternatively excluding upper and lower points over the mean model slope (Figure 11). The coefficients of the three models are reported in Table 3, while pairs and model data are provided in Supplementary material S2 by MATLAB file.

Equation 2 allows estimating the number of two-week WOs (x) depending on *2W-DEU* (y) according to Equation 1 approach, and considering the model coefficients described in Table 3:

$$x = -\left(\frac{1}{b}\right) * ln\left(\left(-c + \frac{a-k}{y}\right)/q\right) \qquad [2]$$

Equation 2 can be used by facility managers to estimate maintenance needs in the considered building context.

3.4. Impact of timetable scenarios on maintenance and occupancy performances

Table 4 shows the expected 2W-DEU (m) in the four alternative timetable scenarios, based on the mean model of Equation 2. Limiting the students’ movement between floors (A, B, D) has a positive impact on 2W-DEU, especially on the elevators connecting the greatest number of floors and the building-block A entrance (A1, A2).

Table 5 compares the expected two-week WOs, according to the three models of Table 3 based on Equation 2, and also offers the expected rounded-up yearly number of WOs (in parenthesis). Scenario C, which is similar to the current timetable, is the worst scenario. Considering this KPI, the expected WOs are more than twice greater than for Scenario A (limiting students’ movement between floors), regardless of the considered model. Scenario B (limiting movement between building blocks) significantly limits the elevator use, with a difference in WOs of about 10% with respect to Scenario A. Finally, Scenario D is the best case, reducing the maintenance needs by up to 65% with respect to Scenario C, thanking the movement limitation between different floors of the same building.

Similarly, concerning the occupancy KPI, Table 6 shows how limiting the students' movement has a strong impact on the OR of the classrooms (especially in Scenario D), as it prevents using "time holes" in the timetable by other students' groups. Therefore, OR decreases.

Figure 12 focuses on the joint analysis of the occupancy and maintenance KPIs and resumes OR-WOs number pairs (considering the mean model descried by the parameters in Table 3 and by the two-week WOs estimated in Table 5) for each timetable scenario. Scenario C, assumed as the reference, is characterized by the highest occupancy ratio and expected two-week WOs. Introducing movement constraints means obtaining a reduction of maintenance needs, but OR is only slightly affected. Although Scenario B is characterized by more relaxed constraints with respect to Scenario A, the results are quite similar in both these scenarios, having OR reduced only to a 3÷4%, with negligible effects on buildings sustainability. Scenario D, characterized by the strongest constraints, has the lowest OR, but the value is only 7% smaller than in Scenario C. Meanwhile, WOs are reduced by about 50% in Scenarios A and B, and up to 78% in Scenario C. The reduction of the number of WOs in the different scenarios may also affect the maintenance costs (Yanbin et al. 2020; Zhang and Zubair 2022). Università Politecnica delle Marche spent about 3000 €/elevator in the last three years period (i.e. 2020-2022) for ordinary maintenance and 3 elevators required extraordinary maintenance for a cost of about 45.000 € in the same period. Considering the 15 elevators in the analysed buildings, strong attention to occupancy data can reduce maintenance costs by 15000 €/year in A and B scenarios and by 23.400 €/year in Scenario C.

4. DISCUSSION

This work defines a data-driven correlation analysis between buildings occupancy (depending on hosted activities) and maintenance issues (focusing on elevators), useful to assess building O&M performances under different scheduling arrangements, and so to support decision-makers in defining sustainable class occupancy strategies.

The results obtained on the investigated case-study, a university campus, show the potential of this approach for optimizing O&M in relation to the organization of activities and occupants' movement in complex buildings. Alternative class timetabling scenarios, depending on imposed limitations to the students' movement, were tested in terms of two main KPIs: the occupancy ratio, which is a measure of the occupancy performance since it defines "how much" the building is used with respect to its maximum capabilities; and the expected number of maintenance WOs for the elevators system, which represents the maintenance performance. In the analysed case, the best timetabling scenario provides a small OR reduction (from 3 to 7%) while entailing a drastic reduction of maintenance needs (until 7 times) with respect to the current reference timetable.

The study suggests the following main findings:

1. the proposed data-driven approach ensures significant correlations between the supposed building use and the maintenance needs, although some simplifications have been made (i.e. using a static model for occupants' movement and elevators' use based on the shortest path principle, and assuming the elevators' use based on the in-situ survey) (Lang et al. 2016). Indeed, such results seem to encourage the possibility to use a quick-to-apply but robust modelling approach to be included in BPS tools to provide preliminary and expeditious assessments of building O&M performances;
2. concerning the occupants' interactions with the elevators, although monitoring activities were performed for a limited duration and by involving about 10% of occupants, results seem to be sufficiently reliable since they confirm that the probability to use the elevator increases with the number of the travelled floors, especially for moving upstairs (Li et al. 2014; Olander and Eves 2011);
3. maintenance performances are confirmed as influenced by hosted students' number and cyclic buildings use for teaching activities, since WOs essentially increase at re-opening and re-starting of building use by students. Thus, sustainable planned maintenance activities should concentrate on preventive actions during the holiday periods, to improve the users' satisfaction when activities restart (Abdul Lateef et al. 2011; Errandonea et al. 2020; Gunay et al. 2019).

In view of these observations, future efforts to overcome current study limitations could be aimed at:

1. modelling occupants’ movement according to the dynamic simulation of students’ flows, thus supplying facility managers with WOs estimation depending on occupants’ behaviour and use dynamics, also according to microscopic and probabilistic standpoints (Dong et al. 2018);
2. overcoming size effects on results, by extending the survey at different times of the year, and additionally increasing the students’ sample dimension. Group effects on elevator use should be also investigated, to overcome the consideration of users as single-moving individuals. This action will support the improvements suggested in the previous point;
3. according to the previous point, extending the WOs collection to a longer period, along with the occupants’ movement analysis. This will increase the accuracy of data analysis, especially if the facility managers will be supported in the inclusion of real-time monitoring data on building use conditions to highlight differences at both short and long periods (e.g. on annual timetabling variations);
4. including additional elements, related to elevators’ use and components stress, within the correlation model. For instance, this work assumes that an elevator call corresponds to a travel. This conservative assumption stresses the users’ interactions with the elevators, since it was not possible to carry out an experimental campaign to detect the number of callings without elevators’ use. Nevertheless, future works should move towards the analysis of such occupants’ behaviour which can increase the impact of mechanical work with electrical work and useless trips, as well as they can provide WOs assessment in respect to the number of floor stops, which can be additional stressors for the equipment.

In view of these perspectives, according to automation and data analytics-based perspectives in O&M (Dong et al. 2018; Gunay et al. 2019; Ward et al. 2019; Xu et al. 2019), integrated and real-time monitoring systems to trace elevator use could supply more reliable data for WOs estimation, but complexities for their installation in existing buildings exist.

A future greater implication of the research approach will be pursued by moving towards other building performances impacting the whole building sustainability during the life cycle. Such issues could be related not only to maintenance, as in the aims of this work, but also to operation (Tukia et al. 2016; Zubair and

Zhang 2020). In this sense, the maintenance of building systems could be combined with performances relating to their operation as well as to the whole building activities organization depending on scheduling (e.g. relation with occupants' comfort and satisfaction; indoor environmental quality; resources and staff allocation; building automation-related issues; energy consumptions). The timetabling effects on this aspect will be modelled on experimental-based data, using the same framework proposed by this work. Secondly, external stressors at both long and short periods, such as pandemics (D'Orazio et al. 2022), can imply different occupants' loads and movement, and so different O&M performances of elevators and other building systems. These topics could be deepened in order to reach an additional optimization of the O&M depending on the contextual conditions of building use. Finally, further studies could also investigate the applicability of the proposed empirical-based algorithm coefficients to other university buildings, such as other building uses.

5. CONCLUSIONS

The sustainability of buildings depends on the interactions between the physical environment, the decision-makers' choices on its management, and the occupant behaviours, presence and movement. In this overall context, maintenance tasks are one of the fundamental aspects to be considered, since possible faults and problems to components and systems impact on the economic, workforce, business continuity, and satisfaction sustainability aspects. At the same time, maintenance needs strongly depend on the way the building is used, according to the managed scheduling. In the literature, the effects of university class timetabling on O&M have not been fully addressed.

This work hence adopts a data-driven approach to jointly optimize class scheduling and corrective maintenance actions required on elevators. In particular, it analyses the correlation between the classroom schedule arrangement of a university and the corrective maintenance actions needed on the elevators, thanks to experimental data collected during a 15 months-long campaign, to evaluate how the class timetable can affect building sustainability performances in terms of occupancy and maintenance.

The proposed approach matches text/data analysis on maintenance requests and a survey on students' behaviours to derive an experimental-based correlation that relates students' movement with maintenance work orders. Correlations were combined with university timetabling software to assess the impact of organization constraints on building occupancy and maintenance needs as Key Performance Indicators. Results point out that it is possible to reorganize the timetable to limit occupants' movement by reducing elevator maintenance needs and guaranteeing proper classroom occupancy.

Although this work just relies on data relating to faults in the elevator systems, the novel approach and its application results provide evidence of the impact that the sustainable management of occupants' flows would have just on one of the components of maintenance performances. Thus, such an approach could be extended to other issues in O&M of large multi-story buildings, characterized by complex uses, and to other building components. Firstly, it could be directly used to move towards the optimization of operation costs, as one of the crucial parts of sustainability for facility managers, by assessing the correlation between energy consumption and occupants' flows due to the timetabling.

Secondly, the proposed data-driven approach could be extended to other kinds of building systems in the general O&M field. In fact, decision-makers could consider the same methodological approach for the other building systems and components (e.g. HVAC, lighting) with which occupants can directly interact, thus pursuing advantages for general building management and resource allocation strategies.

To this end, integrated simulation tools could apply the behavioural drivers to O&M performances and needs by correlating occupants' movements and actions in a predictive manner. Probabilistic-aware approaches should be preferred in terms of users' number, behavioural patterns and fault occurrence. Building automation systems can support the specific algorithm and model development, as well as their validation, by means of data from real-time monitoring of occupants' presence and maintenance requests. Indeed, a correct selection of the building use constraints will allow evaluating if and how the costs due to timetabling/building activities management strategies and maintenance needs can be balanced out.

6. Supplementary materials

Supplementary materials can be found online in ASCE Library (www.ascelibary.org). In particular, they include: the plans of building blocks A and B from the case study (identifying classrooms, paths network between classrooms and to the elevators/staircases, and buildings entrances), in the Supplementary material S1; MATLAB file on Section 3.3 model, in the Supplementary material S2.

7. Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. In particular, supplementary materials have been included to report data on the case study and on the correlation model.

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9. TABLES

***Table 1** List of elevators and their main features.*

Elevator	Building	Served floors number	Number of floors hosting classrooms	Comments
A1	Tower	10	3	
A2	Tower	10	3	
A3	1	4	4	Capacity: 5 people; connects classrooms with library and coffee
A4	1bis	2	-	Not used by students
A5	3A	3	-	Not used by students
A6	3A	3	3	
A7	3B	4	4	
A8	3B	4	4	
A9	PMS	4	4	Limitedly used by students
A10	4	4	4	
A11	5	4	4	Stopped due to works
A12	5	4	-	Not used by students
A13	5	3	2	Limitedly used by students
A1M	BAS	2	2	Limitedly used by students
A2M	BAS	2	2	Limitedly used by students

***Table 2** 2W-DEU (m) for the three occupancy scenarios defined in Section 2.2.1 and experimental WOs number. For each scenario, data are expressed in raw and normalized (*_N) forms, and refer to the elevators included in the WOs analysis depending on their effective use.*

		2W-DEU (m)						**WOs Number**
Elevator	**Building**	**Nominal**	**Nominal_N**	**Critical**	**Critical_N**	**Effective**	**Effective_N**	
A1	Tower	13170	16590	21798	31800	2180	2745	15
A2	Tower	13170	16590	21798	31800	2180	2745	8
A3	1	15020	15020	20280	20280	2730	2730	11
A6	3A	5880	5880	8302	8300	1200	1200	4
A7	3B	3890	4590	6427	7540	820	860	2
A8	3B	2980	4250	4375	6420	570	600	4
A10	4	11070	11070	18229	18220	2040	2040	8

***Table 3** Coefficients of the three logistic regression-based models according to equation 1*

Parameters	Minimum model	Mean model	Maximum model
a	-61.41	-19.97	-3.45
b	17.75	19.78	16.84
c	0.02	0.01	0.00
k	7.68	14.67	3.49
q	0.34	0.52	0.18

***Table 4** 2W-DEU (m) in the four timetable scenarios*

	2W-DEU for each scenario (m)			
Elevators	**A**	**B**	**C**	**D**
A1	10	0	580	0
A2	10	0	580	0
A3	50	470	850	20
A6	0	340	1450	0
A7	460	310	890	430
A8	580	480	800	580
A10	670	200	410	0
Total	**1780**	**1800**	**5560**	**1030**

***Table 5** Expected two weeks (and yearly, in parentheses) WOs, according to the three models in Table 3, under the timetable scenarios.*

Expected two weeks WOs	Scenarios			
	A	**B**	**C**	**D**
Minimum	0.25 (7)	0.28 (8)	0.47 (13)	0.15 (4)
Mean	0.34 (9)	0.33 (9)	0.69 (18)	0.15 (4)
Maximum	0.66 (18)	0.77 (21)	1.14 (30)	0.4 (11)

***Table 6** Expected classroom occupancy under the timetable scenarios.*

	Scenarios			
Classrooms expected occupancy	**A**	**B**	**C**	**D**
Effective allocated lessons (hours)	1842	1850	1908	1794
Maximum allocable lessons (hours)	2400	2400	2400	2400
OR (%)	76.7%	77.1%	79.5%	74.7%

10. FIGURE CAPTIONS

***Figure 1** Research framework including the three main phases of the work and the related referenced sections in the paper. Specific tools used in each phase are marked within the dashed boxes for each step.*

Figure 2 *Plan of the campus hosting the Engineering Faculty of Università Politecnica delle Marche, located in Ancona (Italy), including the main building blocks A and B. The ten buildings included in this study are identified by different colours and codes.*

Figure 3 *Calculation steps for Daily Elevator Use (DEU) assessment.*

Figure 4 *Analysis of students' movement within the buildings: a) example scheme of shortest path (in green) evaluation while moving from A to B (alternative paths in red), depending on corridors (dashed lines) and elevators/staircases; b) excerpt of the Peklo paths network, showing classrooms (black dots), elevators (green dots) and staircases (red dots) associated with identification codes.*

Figure 5 *WO production and management flow.*

Figure 6 *Distribution of the classrooms dimension in terms of seat number.*

Figure 7 *Distribution of students' groups dimension.*

Figure 8 *Distribution of classrooms' occupancy ratio.*

Figure 9 *Questionnaires-based use of stairs (light grey) and elevators (black) in percentage terms. The difference between levels is shown by the number of levels and vertical distance, for moving upstairs (positive) and downstairs (negative).*

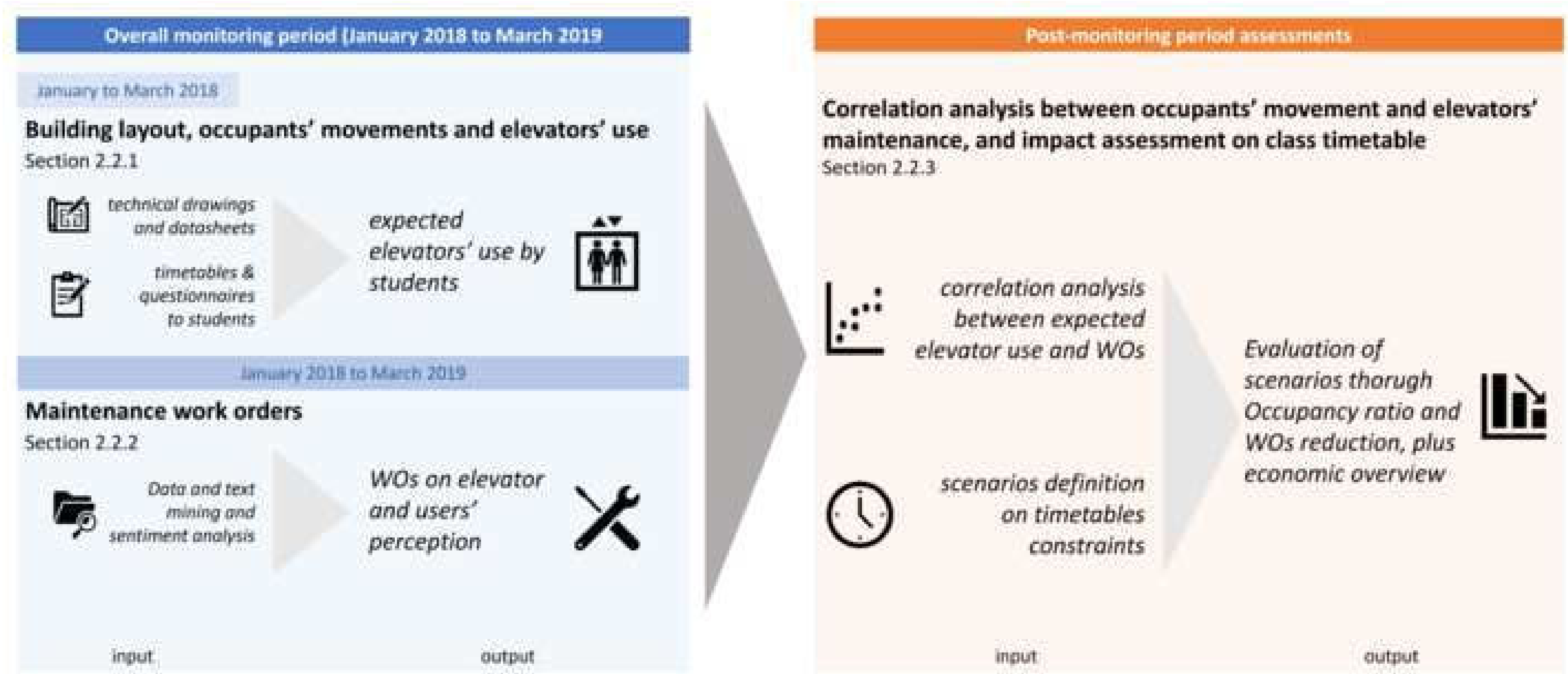
Figure 10 *Monthly WOs trend concerning elevators at Engineering Faculty (monitoring period).*

Figure 11 *Curves representing the obtained mean (black), maximum (red) minimum (blue) models, defined according to Equation 1 and Table 3.*

Figure 12 *Expected two-weeks WO versus Occupancy Ratio OR in the four alternative timetabling scenarios.*

figure 1

Figure1_new.png



Sfondo

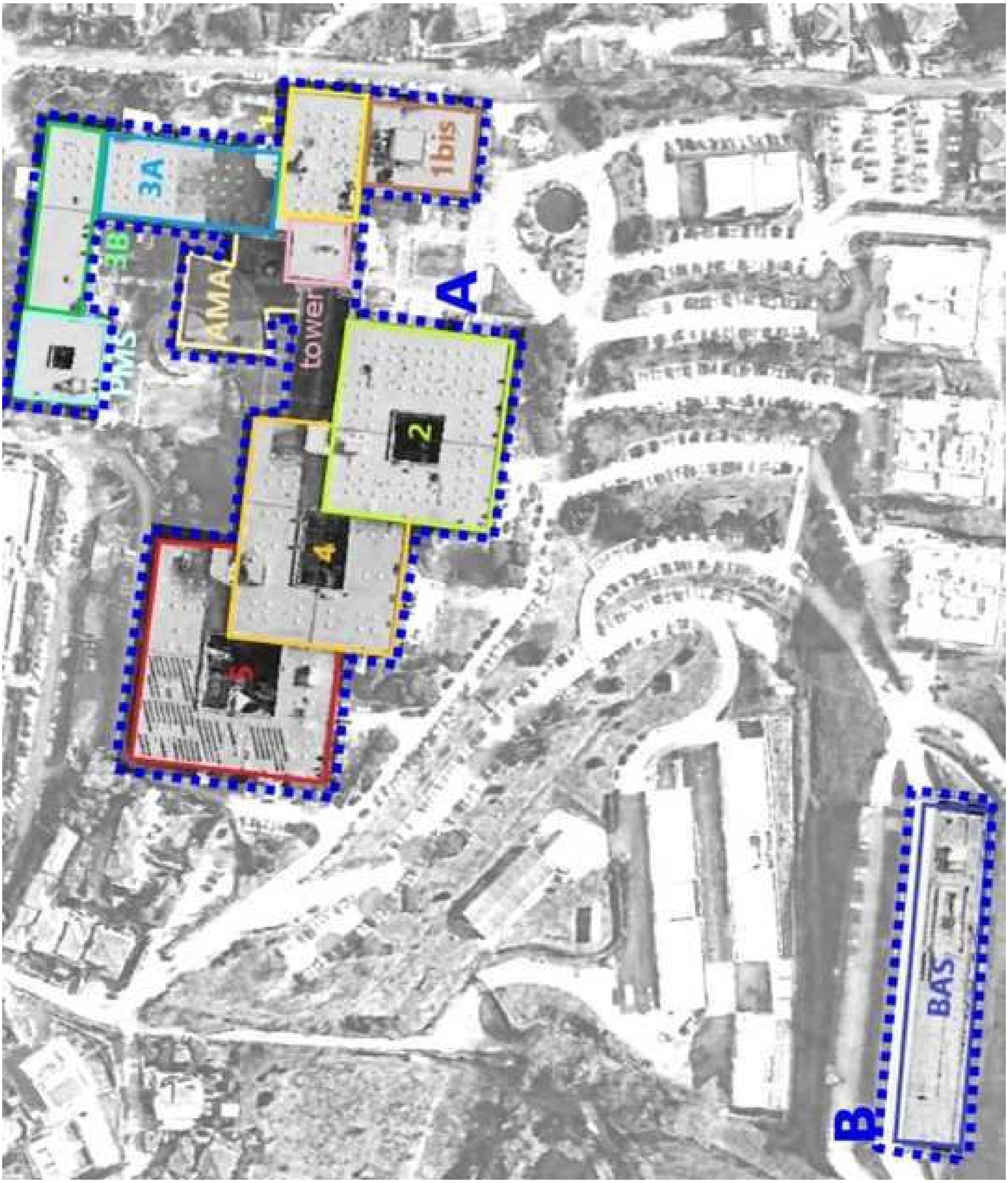


figure 3

figure3_new.png

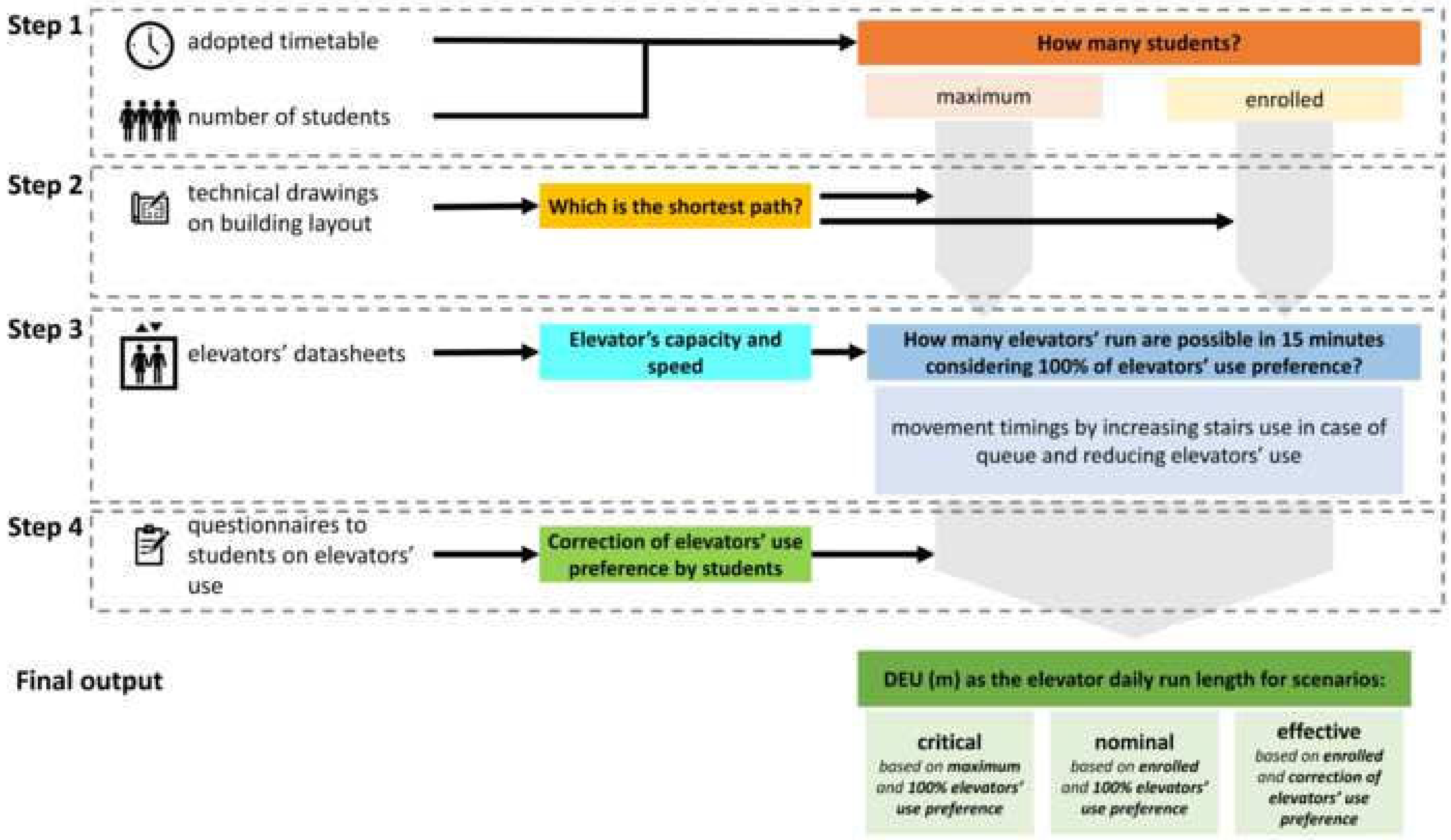
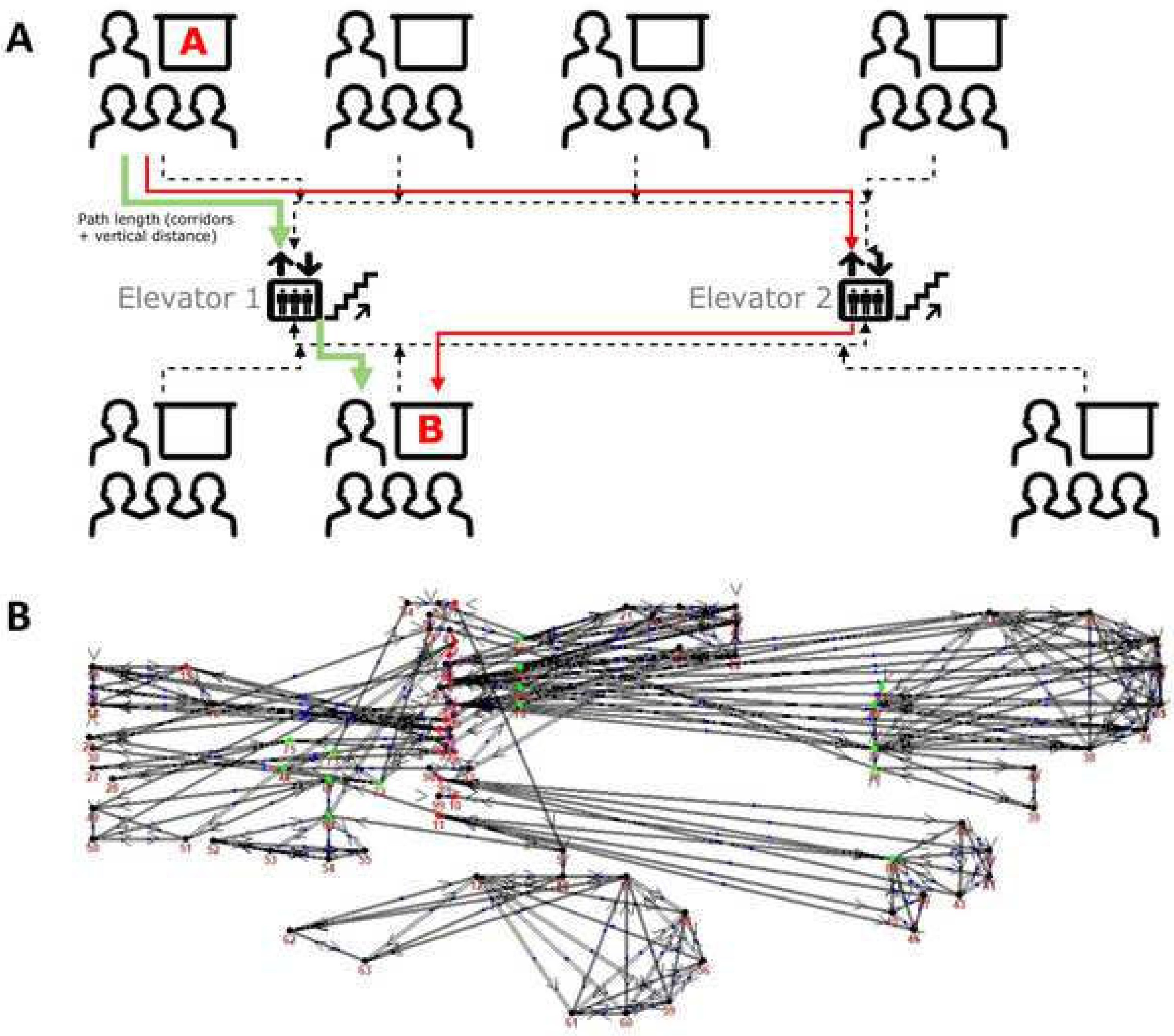


Figure4_new.png



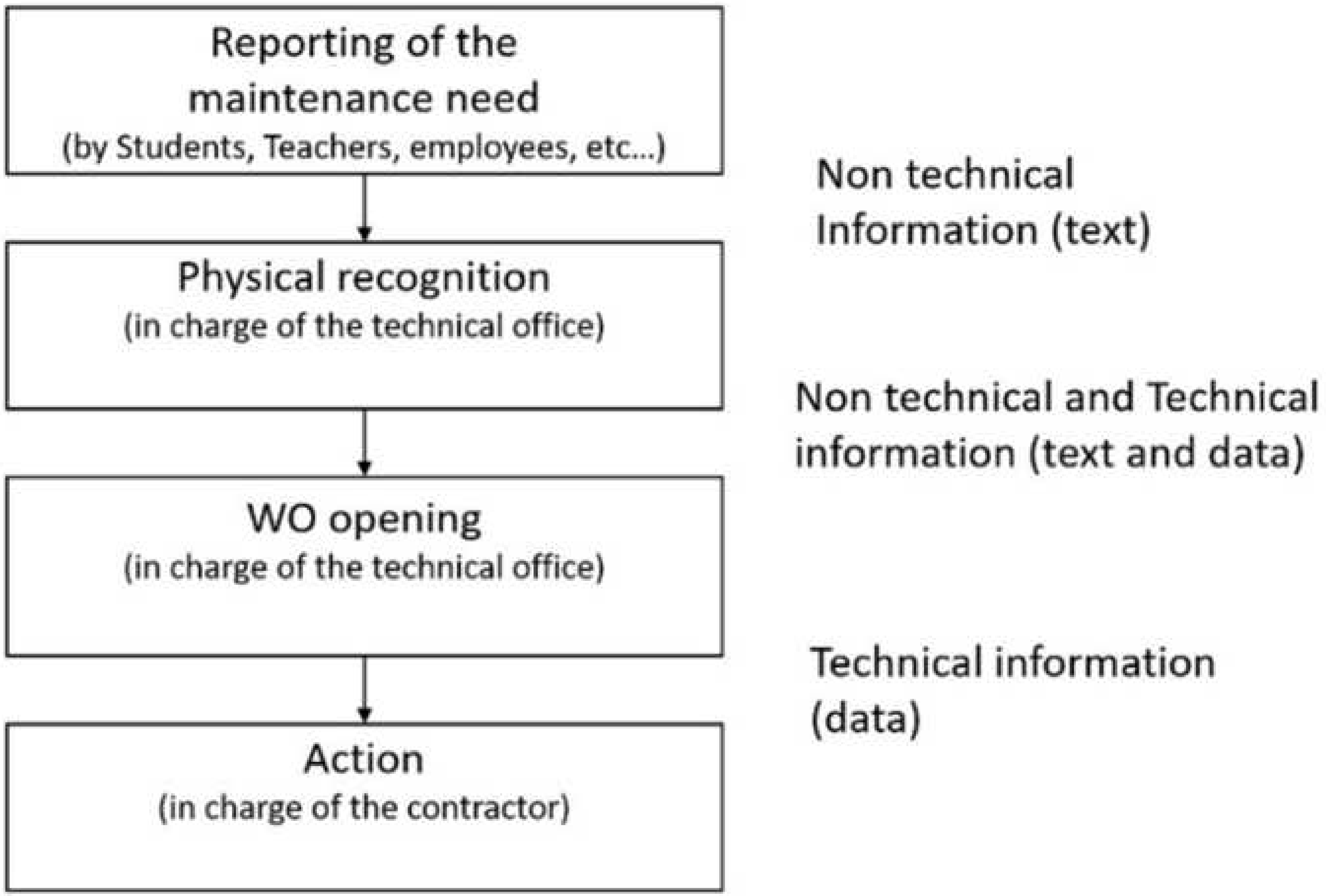

Reporting of the maintenance need
(by Students, Teachers, employees, etc...)
Physical recognition
(in charge of the technical office)
WO opening
(in charge of the technical office)
Action
(in charge of the contractor)
Non technical Information (text)
Non technical and Technical information (text and data)
Technical information (data)

figure 6

figure5.tif

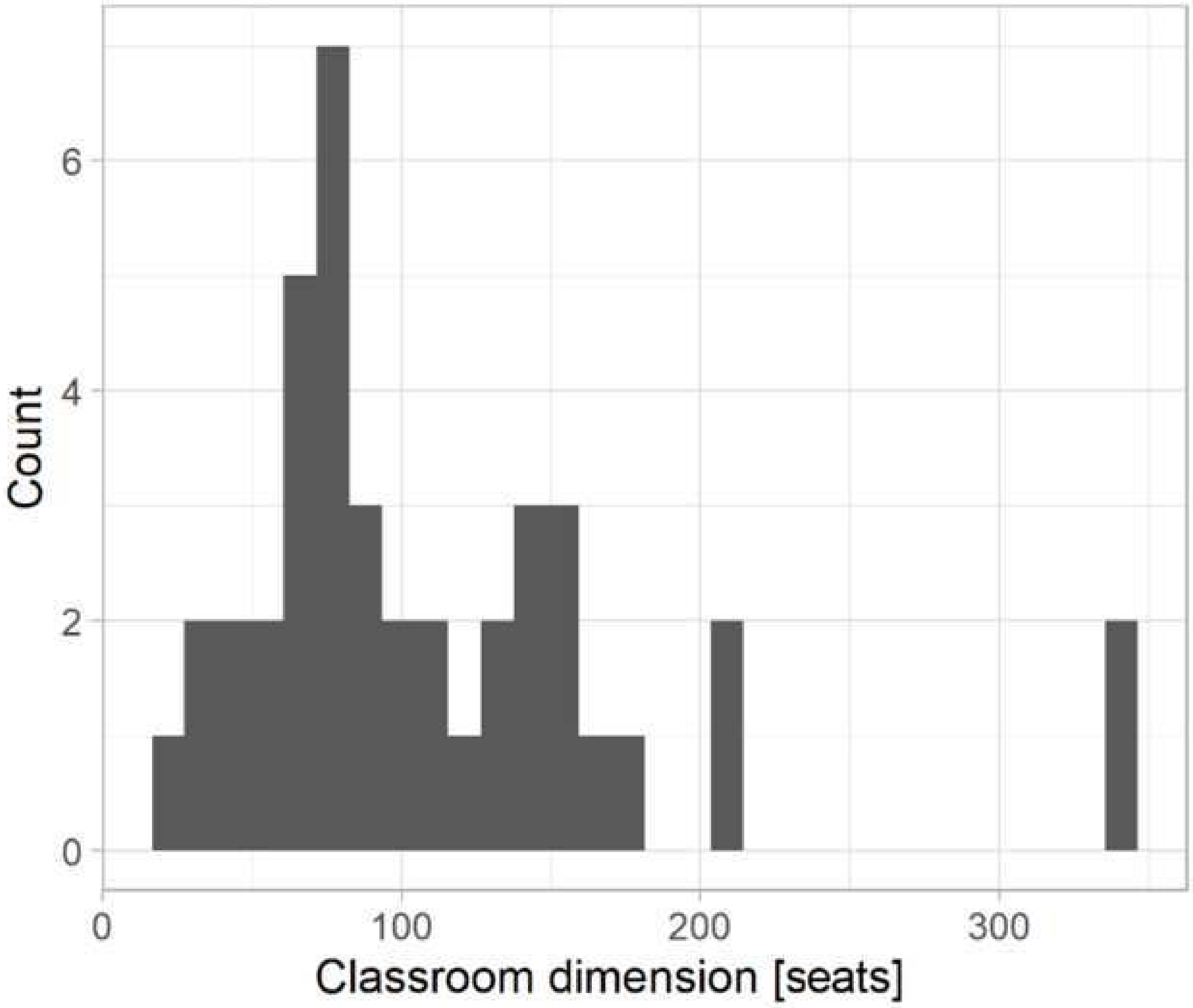


figure 7

Figure7_new.png

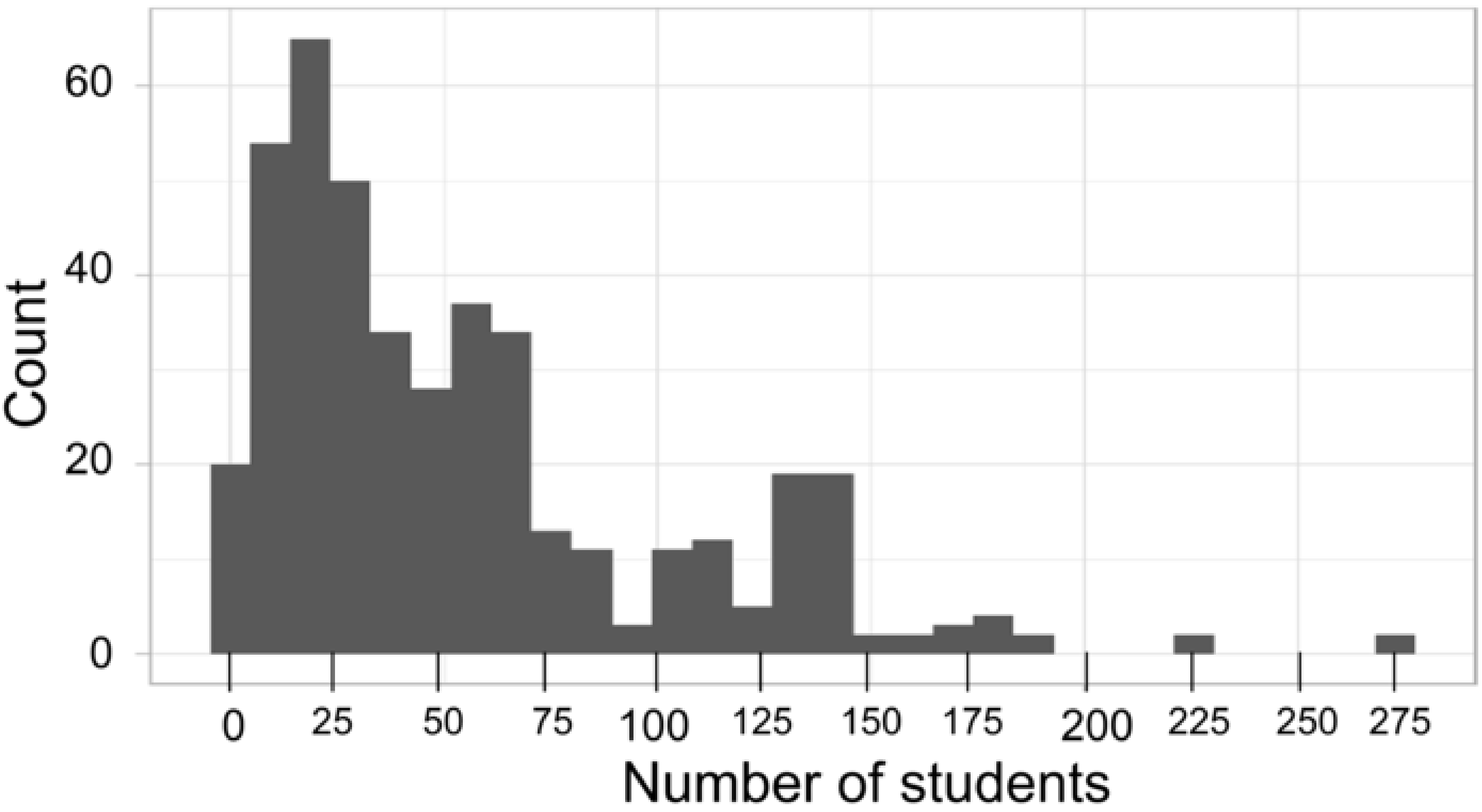


Figure8_new.tiff

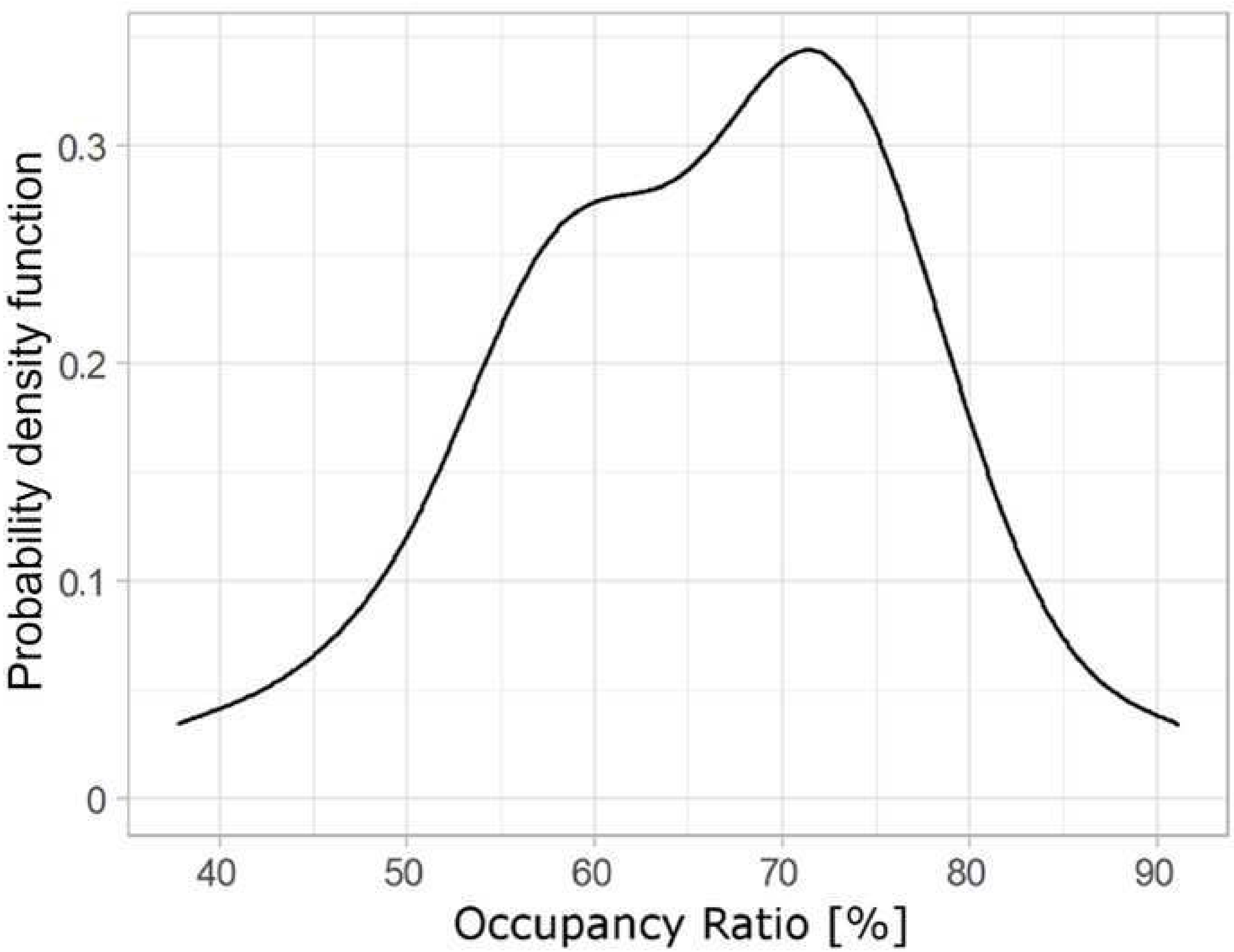


figure 9

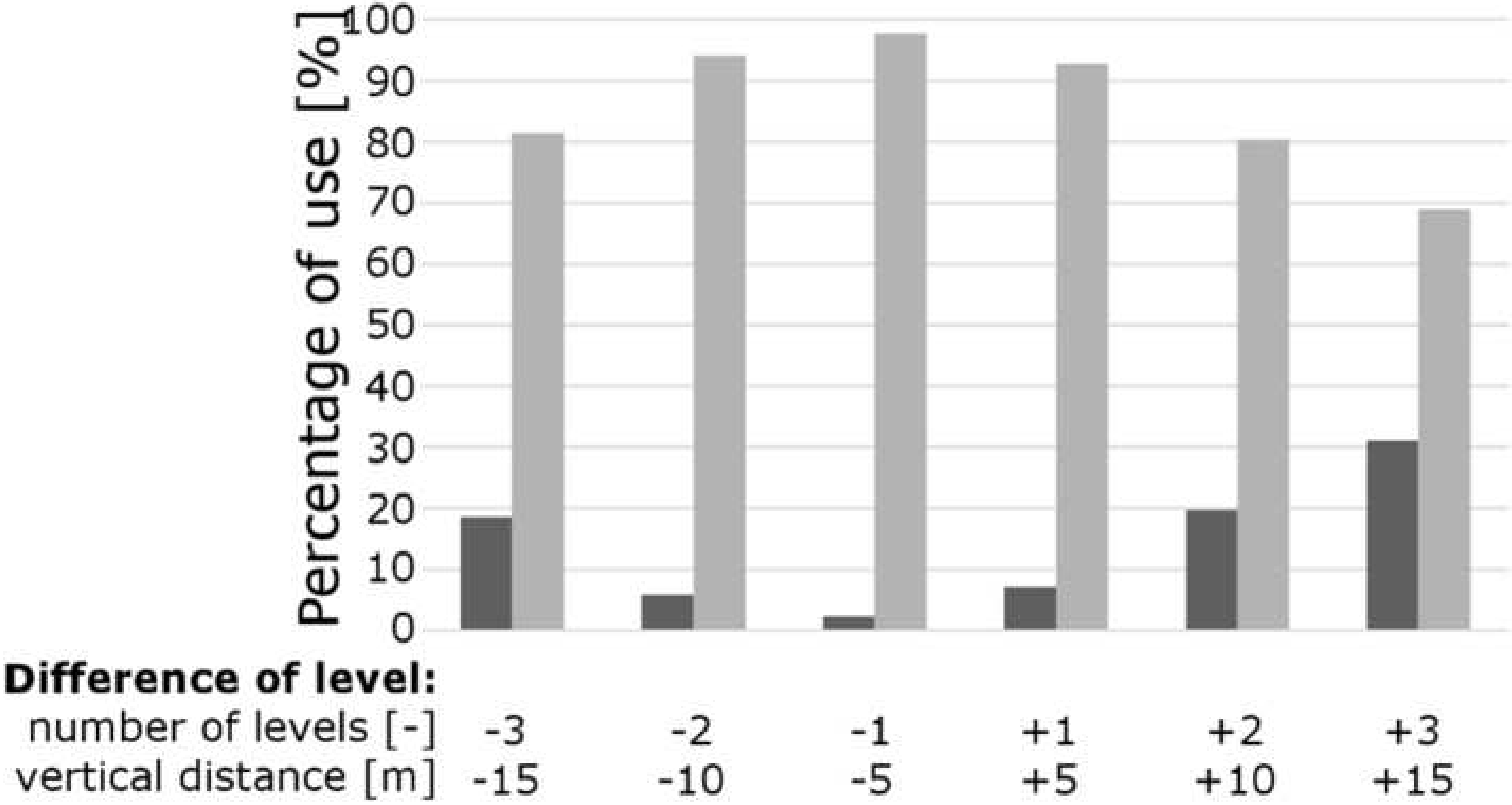

Percentage of use [%]
0
10
20
30
40
50
60
70
80
90
100
Difference of level:
number of levels [-]
vertical distance [m]
-3
-15
-2
-10
-1
-5
+1
+5
+2
+10
+3
+15

Figure10_new.png

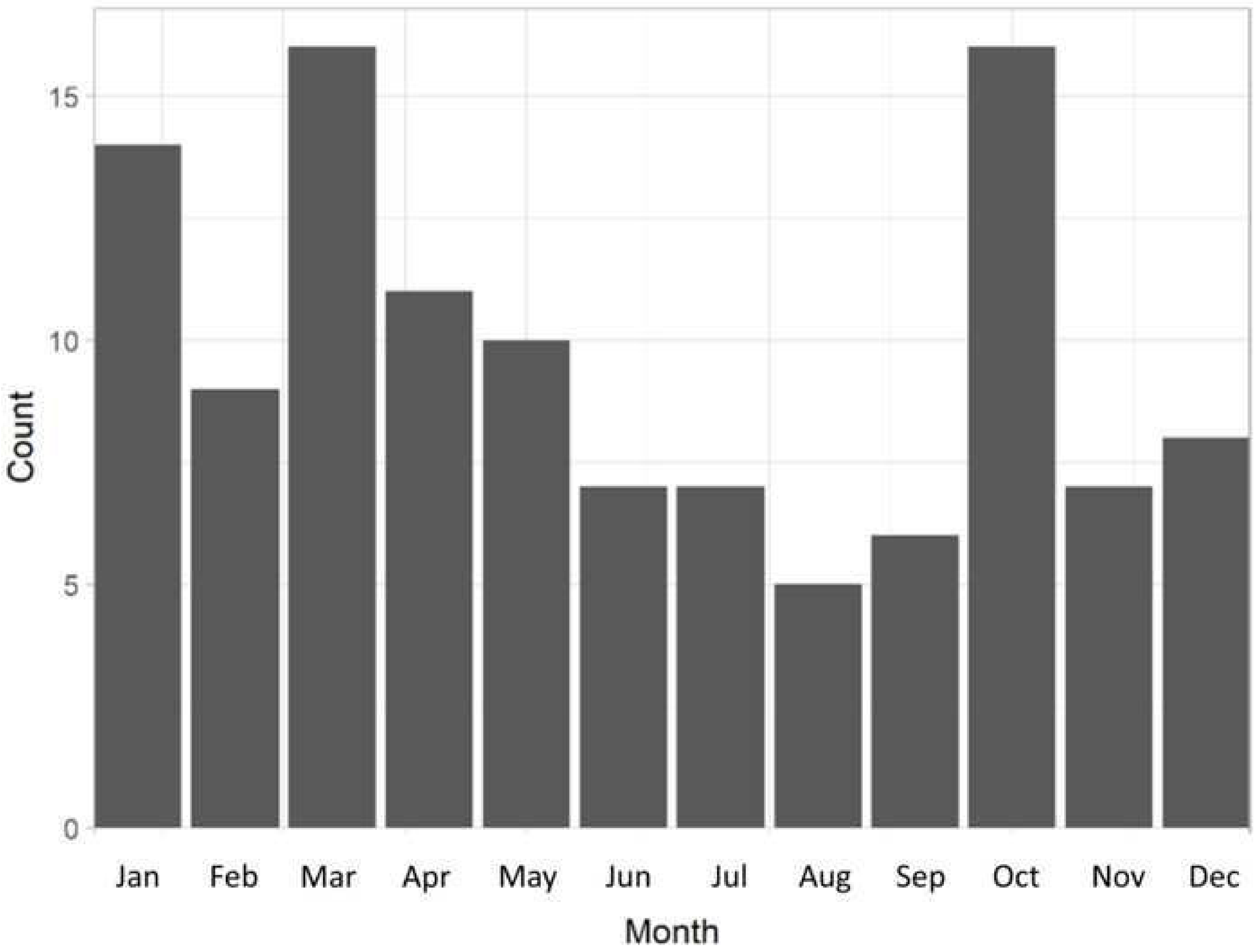


Figure11_new.png

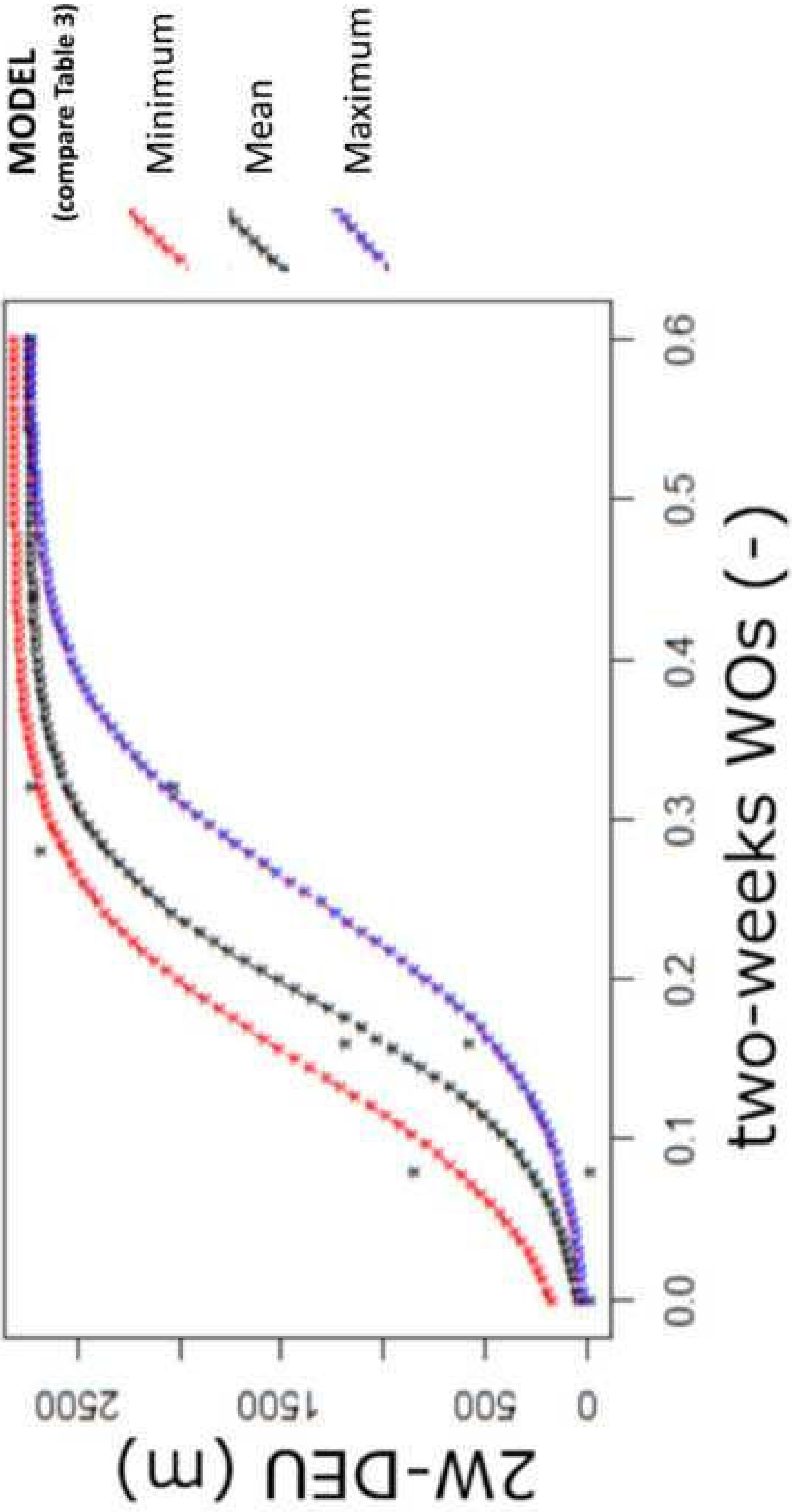


figure11.tif