Transportation
https://doi.org/10.1007/s11116-025-10650-5

Train platforming problem from the viewpoint of passenger flow management

Nattanon Luangboriboon[1] · Marcella Samà[2] · Andrea D'Ariano[2] · Taku Fujiyama[1]

Accepted: 10 June 2025

Abstract

This paper addresses the problem of train platforming problem (TPP) from the viewpoint of passenger management. Currently, the train platforming decision and the passenger management decision are done separately. However, as the train platforming decision can have a significant influence on the path that each group of passengers takes in the station area; hence, the passenger flow in the station should be taken to account when making a platforming decision. In this study, this problem is defined as the Train Platforming and Passenger Management Problem (TPPMP). We propose modelling the TPPMP using a mixed integer linear programming (MILP) formulation. Our case study result suggests that the passenger flow in the station can be improved significantly when trains are allowed to be reassigned to different platforms.

Introduction

Over the years, up until the start of the COVID-19 pandemic, the demand for public transport has been growing continuously, and for railway systems, the ridership in 2019 has increased by almost 20 percent compared to 2015 (UITP 2018, 2022). In the case of London, the number of passengers was reported to exceed the station capacity by almost 10 percent at many stations (DfT 2018). This rapid increase in demand has caused congestion problems on rail networks, and station overcrowding has become one of the major challenges. Overcrowding situations not only reduce passenger comfort but can also increase passengers' safety risks (RSSB 2019, 2005; Atkins 2009). After the COVID-19 pandemic, societal adaptation of remote working has led to certain working days (e.g. Wednesday) seeing demand recover to the pre-covid level, while other working days do not see this trend, which means that railway undertakings need to deal with station congestion problems during peak-periods with

✉ Nattanon Luangboriboon
nattanon.luangboriboon.18@ucl.ac.uk

1 Civil Environmental and Geomatic Engineering, University College London, Chadwick Building, Gower St., WC1E 6BT London, UK

2 Dipartimento di Ingegneria, Università degli Studi Roma Tre, via della Vasca Navale, 79, 00146 Rome, Italy

Published online: 05 July 2025

less budget than before (as the total fare revenue has decreased), thereby requiring agile and smart utilisation of existing infrastructure against the volatility of demand, such as temporal station overcrowding (UITP 2020; Gkiotsalitis and Cats 2021). As the platforming decision can have a great influence on passenger flows in the stations, i.e. the path in the station that passengers will take, and resulting congestion in the station, this would be key to congestion management and smart utilisation of existing space (Luangboriboon et al. 2023).

In practice, train platforming at termini is often managed along with network-level train traffic control, while passenger flow at termini is managed locally and subordinately, and as a result, avoidable station crowding happens at termini. Since overcrowding could lead to safety incidents and train departure delays as well as worsen customer experience, it is ideal to integrate platforming and station crowd management without compromising network-level operations (ORR 2023; Telegraph 2019; Jarvis 2020). Therefore, this study aims to propose a new approach to train platforming that considers both train safety and the optimisation of passenger flow at termini. This integrated problem is defined as the Train Platforming and Passenger Management Problem (TPPMP).

To the best of our knowledge, the proposed TPPMP model is the first to integrate the train platforming problem with the passenger management problem. The model is designed to support platforming decisions while simultaneously improving passenger flow within the station.

In the next section, we review the relevant studies in the literature. Section 3 describes the TPPMP where we define the constraints related to train operation and passenger management. In Sect. 4, we present how the TPPMP is formulated as mixed integer linear programming (MILP). The results of our London Euston station case studies are reported in Sect. 5. The last section concludes the study and suggests what can potentially be done for future research.

Literature review

Train platforming problem (TPP)

With increasing demand, train operator companies face the challenge of accommodating more trains within the existing network and stations. Due to the limited capacity of railway networks and stations, the planning process becomes more and more complex. The existing literature addresses this issue through two related problems: the Train Timetabling Problem (TTP) and the Train Platforming Problem (TPP). While the TTP focuses on scheduling the arrival and departure times of trains, the TPP involves assigning trains to available platforms at stations in a manner that avoids conflicts between trains (Cacchiani et al. 2015). Several previous studies (D'Ariano 2008; Corman et al. 2017; Samà et al. 2017) have also attemp to integrate the TPP with the TTP; however, our research specifically focuses on the TPP aspect.

While the TPP alone can be relatively easy to solve for small stations with a small number of platforms, it can become very complex and difficult for major stations (Caprara et al. 2007; Kroon et al. 1997). Therefore, many researchers have attempted to develop TPP models. A simplified version of TPP, where the train paths are uniquely determined by the platform choice, was studied by Cardillo and Mione (1998). In their study, the TPP is treated as a graph-colouring problem. The same problem was studied by Billionnet (2003) which proposed formulating the graph-colouring problem as an integer linear program (ILP). While Cardillo and Mione (1998) solve their problem using a heuristic method, Billionnet (2003) used an exact algorithm to solve their problem. It was argued that the graph-colouring method is not suitable for complex stations where trains can have many alternative paths to/from platforms and the formulation cannot include the path preference (Lusby et al. 2011). Sels et al. (2014) address the TPP from a planning perspective, where the authors attempted to identify how many extra trains can be added to the current schedule. The concept of fictive routes and platforms was introduced, where they are used to hold overflow trains that cannot be platformed. Similarly, Zwaneveld (1996) focused on identifying the maximum number of trains that can be scheduled through a station. An extension of the former model is presented in Zwaneveld et al. (2001) where they include the platform and path preferences in the model. A more general version of TPP was addressed by Caprara et al. (2011) where the authors formulate TPP as mixed integer linear programming (MILP) and introduce hard and soft constraints to the problem. The hard constraints model the incompatibilities that must be forbidden, e.g. assigning two trains to the same platform at the same time, while the soft constraints are related to the decisions that are allowed but should be penalised. The objective is to minimise the soft incompatibility penalty.

While the research mentioned above assumed a fixed train schedule, there could be unforeseen disruptions that cause the trains to deviate from their original schedule. Carey and Carville (2003) suggested that such problems can be too computationally complex to solve. Hence, they develop a scheduling heuristic that is analogous to the traditional method applied by human train planners. In Carey and Crawford (2007), this method is extended for a multi-station problem. Chakroborty and Vikram (2008) address this problem by developing a MILP model that takes into account train delays and platform reassignments. A heuristic approach was presented by Zhang et al. (2020) to solve the problem presented in Chakroborty and Vikram (2008) to allow it to be used for real-time optimisation. While in Chakroborty and Vikram (2008); Zhang et al. (2020) trains are only separated by headways, Lu et al. (2022) took a unified aggregate approach to represent the interlocking mechanisms for a more detailed formulation.

Passenger flow management

While modern technologies allow trains to run at higher speeds and frequencies, the capacity of stations is still limited. Expanding station capacity, particularly in city centres, poses challenges due to constraints such as limited physical space, lengthy construction periods and the high cost of investment (Oberlander 2014). Consequently, stations are becoming severely overcrowded and it becomes crucial that passenger flows are managed efficiently to maximise the usage of existing spaces and ensure passenger safety.

Within the field of pedestrian dynamics, the *fundamental relationship*, has been extensively studied. This fundamental relationship describes the relation between pedestrian speed, flow and density. The fundamental relationship highlights that in high-density situations, the walking speed and overall flow of passengers can be significantly reduced (Fruin 1971; Virkler and Elayadath 1992; Wong 2010; Daamen and Hoogendoorn 1828; Luangboriboon et al. 2021).

When passenger flows merge, such as at intersections or bottlenecks, the walking speed can be further impacted, potentially leading to dangerous situations like *stampedes* (Zhang et al. 2011; Craesmeyer and Schadschneider 2014; Shiwakoti et al. 2015; Shi et al. 2016). The risk of such situations is heightened when the merging flows are in bi-directional movement (Lam et al. 2003; Liu et al. 2014; Flötteröd and Lämmel 2015). Several guidelines on crowd management in public transport stations state that bi-directional flow scenarios may pose a risk to safety within stations (RSSB 2019, 2005; LU 2019; NetworkRail 2011). Therefore, in order to effectively manage passenger flows and maintain safety, it is recommended that such situations should be actively avoided.

To actively manage the flows of passengers, there exist various passenger management measures typically used by practitioners (Mensink 2017; Hoogendoorn 2010; Oberlander 2014). These measures aim to ensure adequate safety levels and efficient passenger management within stations. However, it is important to note that certain measures, such as limiting inflow and passenger holding, may potentially have negative impacts on the quality of service (Wang et al. 2015). Therefore, careful consideration and planning are required to prevent adverse effects and maintain a satisfactory level of service for passengers.

Research in the field of passenger flow and demand management can be broadly categorized into two main streams. The first focuses on *train scheduling/rescheduling*, aiming to develop adaptive strategies for adjusting train services in response to fluctuating passenger demand. The second stream focuses on *passenger flow control*, which seeks to establish effective strategies for managing passenger movements within railway stations. A summary of these research efforts is presented in Table 1.

Gaps and contributions

As the platforming decision is closely related to the incoming/outgoing paths of each train to/from the station, the existing research on TPP generally focuses mainly on avoiding conflicts of trains at the platforms, i.e. preventing more than one train from occupying the same platform at the same time, and between train paths. However, the platforming decision influences not only the train paths but also passenger circulation and the resulting congestion inside the station. To our knowledge, passenger flow management has not been addressed in any previous TPP studies. Addressing passenger flow management as a TPP problem would practically reduce station overcrowding and academically add a new dimension to the TPP literature. In this study, we aim to address this gap by proposing a new problem formulation method that integrates the TPP with the passenger flow management problem. The problem will be presented as TPPMP, which aims to allow the infrastructure managers to safely assign trains to appropriate platforms while also allowing passenger flow management to be done safely and efficiently.

Problem description

In this study, we aim to propose a new approach to TPP that considers not only the aspects of train operation but also the optimisation of passenger flow in the station. To achieve this integration, it is crucial to have a comprehensive understanding of the constraints associated with train operations and passenger movement in the station area. Additionally, beside

Table 1 Passenger flow and demand management research

Publications	Method	Objective	Model
Wang et al. (2018)	Train Scheduling/Rescheduling	Passenger waiting time	Integer nonlinear programming
Wang et al. (2015)	Train Scheduling/Rescheduling	Passenger delay	Mixed integer programming
Barrena et al. (2014)	Train Scheduling/Rescheduling	Passenger waiting time	Mixed integer programming
Niu and Zhou (2013)	Train Scheduling/Rescheduling	Passenger waiting time and remaining passengers	Nonlinear programming
Niu et al. (2015)	Train Scheduling/Rescheduling	Passenger waiting time	Integer nonlinear programming
Sun et al. (2014)	Train Scheduling/Rescheduling	Passenger waiting time	Mixed integer programming
Xu et al. (2016)	Passenger flow control	Station service capacity	Simulation-based
Li and Zhou (2013)	Passenger flow control	Transfer efficiency	Simulation-based
Wang et al. (2015)	Passenger flow control	Passenger delay	Mixed integer programming
Yuan et al. (2022)	Passenger flow control	Passenger waiting time	Mixed-integer non-linear programming
Meng et al. (2020)	Passenger flow control	Passenger waiting time	Integer linear programming
Corman (2020)	Train Scheduling/Rescheduling & Passenger flow control	Passenger waiting time	Game Theory
Li et al. (2017)	Train Scheduling/Rescheduling & Passenger flow control	Minimises the time-table and the headway deviations	Quadratic programming
Shi et al. (2018)	Train Scheduling/Rescheduling & Passenger flow control	Passenger waiting time	Integer linear programming

these constraints, we also defined some regulation measures which specify how passengers should be managed in order to achieve maximum efficiency and passenger satisfaction.

Train operational constraints

Regarding the TPP, each train is assigned to a platform according to the following operational rules (NetworkRail 2021). First, it is important that no more than one train is assigned to the same platform at the same time. Second, there should be a minimum headway separation H between the train departing and the train arriving at the same platform to prevent conflict between the two vehicles. Third, we must consider the physical feasibility of the platform. This includes the platform length (which must not be shorter than the train) and the rolling stock requirements (the platform height, the loading gauge, the power supply system (AC/DC difference), etc.). Fourth, we must also consider the route availability, i.e. whether a platform is connected to the required incoming/outgoing track. Finally, consideration also needs to be given to passenger service requirements (certain trains need to go to certain platforms because of the presence of specific passenger service requirements such as ticket barriers, accessible facilities, immigration control, etc.).

Passenger constraints

On the passenger side, while passenger flows are generally viewed as continuous in the existing study of passenger crowd management in railway stations (Xu et al. 2016; Li et al. 2017; Wang et al. 2015), it was suggested that this assumption is only appropriate for stations with a simple layout and with fixed platform allocations (e.g. metro and urban railway stations) (Luangboriboon et al. 2023). In these stations, passengers would generally proceed to their platforms immediately as they arrive at the station, and hence the flow of passengers is distributed evenly over time, i.e. continuous flow. On the contrary, for stations where the allocation of platforms is not fixed, i.e. mainline railway stations, passengers are generally held in the concourse until platform numbers are announced and they are allowed to go to platforms just before train departure (in a similar way to airports). Therefore, passenger flow in mainline railway stations can be viewed as discrete instead.

As passenger flows are viewed as discrete, in this study, passengers who are travelling to/from the same service can be seen as a group. Although there may be variations in walking speeds among individual passengers within each group, the majority of each group would walk at a relatively consistent speed. The majority of passengers in each group can be regarded as concentrated areas of high density. It is these high-density pockets which will be mainly focused on, due to their critical role in generating congestion. Generally, passengers would travel between the concourse and their platforms; hence, the path that each group will travel through is decided by the platform decision. We divide a station into a number of areas; hence, the path of each passenger group would be a specific sequence of areas.

Besides the train operational rules, there are also rules regarding passengers, which are to ensure that the formulation is accurate and also to maintain passenger safety and comfort. A specific amount of time is required for each group of passengers to travel through each area. The travel time can be divided into two major components: *passing time* and *clearing time*. The passing time is the time required for the first passenger in a group to traverse through an area. Given v is the passenger's walking speed, the passing time p can be calculated as $p = l/v$, where l is the length of the corresponding area. The length l of any corresponding areas is measured as a straight line, assuming passengers will use the shortest route available, from the entry point to the exit point of that area. The clearing time is the time required for the rest of the passengers in a group to exit an area after the first passenger has exited. The clearing time c depends on the passenger's walking speed v, the number of passengers in a group n, the passenger's density d and the width of the corresponding corridor w, and it can be calculated as $c = n/(v \times d \times w)$. Additionally, as soon as passengers reach the end of an area, they will immediately proceed to the subsequent area. Although some passenger holding measures may be available, e.g. using temporary barriers, it is not practical and will not be considered in this study.

Passenger regulation measures

In narrow corridors or platform areas, a merge of passenger flow could significantly reduce the flow. Particularly in bi-directional conditions, which could lead to congestion, blockages, and even hazardous situations such as 'stampedes'. To ensure passenger safety and efficient flow, it is crucial to prevent *conflict situations* where multiple groups of passengers occupy the same area simultaneously, as it can pose challenges in terms of passenger management and safety. Figure 1 illustrates a potential conflict scenario. In this scenario, passengers from Group A are alighting from their train at Platform 1 (PF1), while passengers from Group B are heading towards their train at Platform 2 (PF2). Areas 1, 2, and 3 represent the locations where these two groups could potentially conflict with each other, i.e. both groups can be in the same area at the same time. To prevent such conflict situations, management actions are required.

At the platforms, before trains arrive, there is a risk of passengers falling onto the tracks, especially if the platform area is crowded and they have to wait for a long time while the track is empty. After train arrival, there are other operations activities on the platform areas, including cleaning, catering and service setups, which may involve the use of trolleys or small vehicles. The presence of passengers not only obstructs these operations but can also lead to accidents where passengers are harmed. Therefore, for safety purposes, we aim to delay passengers being on platforms until the area is prepared. This can be done by holding passengers in the concourse area, with the assumption that passengers will wait in the concourse area and will only proceed to the platforms when their platform numbers are announced as shown in Fig. 2. In other words, the passenger timing can be controlled using the platform number announcement.

By holding passengers in the concourse, passengers may not be able to board their trains on time, causing a departure delay. This delay caused by the management decision is measured as the *Total Tardiness* (*TT*), i.e. the total amount of delay. According to our previous study (Luangboriboon et al. 2023), although, with careful and thorough consideration, the passenger management actions would still result in a certain amount of *TT*, mainly due to station crowd management measures intended to avoid conflict among passenger groups that are travelling to/from nearby platforms with intersected paths. As mentioned previously, the platforming decision has a significant effect on the path that each group of passengers will take; consequently, it will also have a great influence on the resulting amount of *TT*. Some platforming decisions may result in significant *TT*, while for others they may allow passengers to be managed according to all constraints without causing any delay.

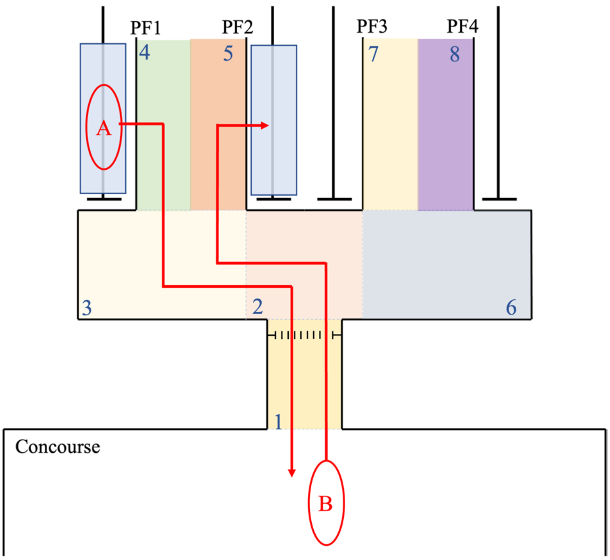

Fig. 1 Potential conflict situation

Fig. 2 Passengers waiting for platform number announcement

Therefore, in this study, we aim to integrate TPP with the passenger management problem as TPPMP. The TPPMP can be defined as the problem of assigning the appropriate platform to each train in a way that complies with all rules (regarding train operation and the passengers) that would eliminate or reduce *TT* as much as possible.

It should be noted that, without the passenger management actions, these service delays could be avoided. However, this can potentially result in passenger conflict. The use of *TT* as an objective function, in this case, can also be used to represent the level of conflict that could potentially occur due to the specified platforming decisions.

Problem formulation

The TPPMP can be seen as a job shop scheduling problem (JSP) which can be formulated as a mixed-integer linear programming (MILP) problem. This formulation method is inspired by the Alternative Graph (AG) model, which has been used to formulate both passenger management problems (Luangboriboon et al. 2023) and railway scheduling problems (D'Ariano et al. 2007, 2014; Samà et al. 2017; Corman et al. 2017; Corman 2020; Corman et al. 2010).

In our formulation, each group of passengers and/or each train service is considered a *job*, denoted with *k*. The spaces (station areas/track sections) that passengers/trains can occupy are considered as *resources*, *j*. As each train may be able to go to several platforms and the chosen platform would influence the route that passengers will take inside the station, we denote the chosen platform, as well as the passenger/train route towards/from the chosen platform, as *r*. A utilisation of a resource by a job, e.g. passenger passing through an area, is defined as an *operation*o_{krj}. Each operation o_{krj} is associated with a start time t_{krj} which is the entrance time of passenger group/train service *k* in resource *j* when going to/from platform *r*. There are also operations o_0 which represent the starting of the schedule, i.e. $t_0 = 0$.

Each route *r* may consist of several resources that passengers/trains travel through. These resources must be traversed in a specific sequence, i.e. set of operations that have to be processed in a specific order, this is to reflect the physical sequence of areas which is not possible to be traversed otherwise. These sequences can be modelled using *fixed constraints*. Let area *j* be the subsequent area of area *i* on the route *r* of job *k*, the fixed constraints $t_{krj} - t_{kri} \geq p_{kri}$ is used to represent the sequence, while p_{kri} is the minimum time required for a passenger to travel through area *i* and reach area *j*, i.e. passing time. In an area where passengers cannot be held, the passing time will also be the maximum time allowed for a passenger to go through that area as well, i.e. $t_{kri} - t_{krj} \geq -p_{kri}$.

We denote the set containing all fixed constraints as F, and the constraint $t_{krj} - t_{kri} \geq p_{kri}$ is denoted with $(kri, krj) \in F$. In set F there can also be a fixed constraint $t_{krj} - t_0 \geq e$($(0, krj) \in F$), where *e* is the earliest time that the platform number for departure service *k* is allowed to be announced and *j* is the area adjoining the concourse area. This is to prevent passengers from being on the platform too early.

To prevent passengers/trains from conflicting (using the same resource at the same time), *alternative constraints* are used. A pair of alternative constraints can be used to represent the minimum separation and the sequencing decision needed between two jobs (groups of passengers/trains) that use the same resource (area/track section). Given o_{kri} and o_{krj}(o_{lsm} and o_{lsn}) are two consecutive operations. If *i* and *m* are the same resource, operations o_{kri} and o_{lsm} cannot be processed at the same time. To prevent this conflict, it is necessary to maintain a minimum separation between t_{kri} and t_{lsm}. If operation o_{kri} is chosen to be processed first, operation o_{lsm} has to wait until operation o_{kri} is completed, i.e. job *k* has all cleared out of area *i*, and vice versa. The completion time of operation o_{kri}(o_{lsm}) is the time when job *k* (*l*) reaches the subsequent area *j* (*m*) plus the clearing time/headway separation, i.e. $t_{krj} + c_{kri}$($t_{lsn} + c_{lsm}$). Hence, it could be formulated with a pair of constraints $t_{lsm} - t_{krj} \geq c_{kri}$ and $t_{kri} - t_{lsn} \geq c_{lsm}$. A set containing all pairs of alternative constraints is denoted as *A*, and a pair of constraints $t_{lsm} - t_{krj} \geq c_{kri}$ and $t_{kri} - t_{lsn} \geq c_{lsm}$ is denoted as $((krj, lsm), (lsn, kri)) \in A$. Exactly one of the constraints from each pair has to be selected for a feasible schedule.

Furthermore, let operation o_{abu} represents the arrival of train *a*, as well as the passengers, at track section *u* adjacent to platform *b*. As passengers alight from the train, there will be two subsequent operations to operation o_{abu}, namely, o_{abv} and $o_{abu'}$. Operation o_{abv} represents passenger group *a* alighting onto area *v* when using the route *b*, while operation $o_{abu'}$ represents train *a* leaving track section *u*. Given operation o_{wxy} is an operation associated with passenger group *w* boarding train *y* at platform *x*, and train *a* and *y* are the same train. In our formulation, job *a* is considered to vacate resource *u* when job *w* starts boarding train *y* (job *w* starts occupying resource $y = u$ instead). Hence, $t_{abu'} = t_{wxy}$. However, for formulation purposes, this constraint will be formulated as two fixed constraints: $t_{abu'} - t_{wxy} \geq 0$ and $t_{wxy} - t_{abu'} \geq 0$. Additionally, there should also be fixed constraints $t_{abu} - t_{abv} \geq 0$ and $t_{abv} - t_{abu} \geq 0$, as passengers should be able to alight as soon as their train arrives at the platform, i.e. $t_{abu} = t_{abv}$.

In the case where two trains join and form a new service (i.e. coupling), the formulation can be done similarly. However, the alternative constraints that represent the potential conflict between these two trains at the track section resource are removed (to allow two trains to join). For the decoupling cases, these alternative constraints representing conflicts between the one arrival and two departure services are also removed. Given train *a* is formed of trains *y* and y'. Let operation $o_{w'xy'}$ be passenger group w' boarding train y' at platform *x*. The constraints $t_{abu'} - t_{wxy} \geq 0$ and $t_{wxy} - t_{abu'} \geq 0$($t_{abu'} - t_{w'xy'} \geq 0$ and $t_{w'xy'} - t_{abu'} \geq 0$) are only applied if train *y* (y') depart later than the other train. Instead, there will be two additional constraints: $t_{wxy} - t_{abu} \geq 0$ and $t_{w'xy'} - t_{abu} \geq 0$, i.e. job *w* and w' cannot depart before job *a* arrives.

For operation o_{wxy} which represents passenger group *w* boarding train *y* at platform *x*, the subsequent operation o_{wxz} would represent the train departure, i.e. departure time is t_{wxz}. Let d_w be the scheduled departure time of job *w*. If job *w* departs after its scheduled time, we represent the delay as the tardiness $td_w = max\{0, t_{wxz} - d_w\}$. Let *D* be a set containing all departure jobs. The objective function, i.e. minimising the total tardiness *TT* can be described as $TT = \sum\limits_{w \in D} td_w$.

To formulate fixed and alternative constraints that include all possible train and passenger routes, we introduce a *big-M* constant, which is a sufficiently large constant, e.g. the sum of all passing time. For each pair of alternative constraints $((krj, lsm), (lsn, kri)) \in A$, we introduce a binary variable $g_{kri\_lsm} \in \{0, 1\}$. This alternative constraint can be formulated as an MILP as follows:

$$t_{lsm} - t_{krj} + M(1 - g_{kri\_lsm}) \geq c_{kri} \tag{1}$$

$$t_{kri} - t_{lsn} + M(g_{kri\_lsm}) \geq c_{lsm} \tag{2}$$

$$g_{kri\_lsm} \in \{0, 1\}. \tag{3}$$

If operation o_{kri} is selected to be processed before operation o_{lsm}, the binary variable $g_{kri\_lsm} = 1$, i.e. the constraint $t_{lsm} - t_{krj} \geq c_{kri}$ is enforced. While $g_{kri\_lsm} = 0$, if otherwise.

In the case where trains can be assigned to more than one platform, a binary variable $h_{kr} \in \{0, 1\}$ is introduced. Given operations o_{kri} and o_{krj}, which are two consecutive operations of job *k* to/from platform *r*. The fixed constraint $t_{krj} - t_{kri} \geq p_{kri}$ is only enforced if platform *r* is selected. This can be formulated as follows:

$$t_{krj} - t_{kri} + M(1 - h_{kr}) \geq p_{kri} \tag{4}$$

$$\sum_{r=1}^{R_k} h_{kr} = 1 \tag{5}$$

$$h_{kr} \in \{0, 1\} \tag{6}$$

$$h_{kr} = h_{k'r}, \text{for job } k \text{ and } k' \text{ which use the same train.} \tag{7}$$

If platform *r* is selected, the binary variable $h_{kr} = 1$, and $h_{kr} = 0$ if another platform is selected. Additionally, R_k is the number of platforms that job *k* can possibly be allocated to. As only one platform can be selected for each job; therefore, $\sum_{r=1}^{R_k} h_{kr} = 1$. For two jobs that use the same train (*k* and k'), they must depart/arrive on the same platform, hence the constraint $h_{kr} = h_{k'r}$.

As for alternate constraints, a pair $((krj, lsm), (lsn, kri)) \in A$ is only enforced if platform *r* is selected for job *k* and *s* is selected for job *l*. This can be described as:

$$t_{lsm} - t_{krj} + M(1 - g_{kri\_lsm}) + M(2 - h_{kr} - h_{ls}) \geq c_{kri} \tag{8}$$

$$t_{kri} - t_{lsn} + M(g_{kri\_lsm}) + M(2 - h_{kr} - h_{ls}) \geq c_{lsm} \tag{9}$$

$$\sum_{r=1}^{R_k} h_{kr} = 1 \tag{10}$$

$$\sum_{r=1}^{R_l} h_{ls} = 1 \tag{11}$$

$$g_{kri\_lsm} \in \{0, 1\} \tag{12}$$

$$h_{kr}, h_{ls} \in \{0, 1\}. \tag{13}$$

Let *J* be a set containing all jobs in the focus time horizon, the TPPMP can be formulated using the MILP formulation as follows:

$$\text{minimise } TT = \sum_{w \in D} td_w \tag{14}$$

$$\text{s.t. } t_{krj} - t_{kri} + M(1 - h_{kr}) \geq p_{kri} \forall (kri, krj) \in F \tag{15}$$

$$t_{kri} - t_{krj} + M(1 - h_{kr}) \geq -p_{kri} \quad \forall (kri, krj) \in F \tag{16}$$

$$t_{krj} - t_0 + M(1 - h_{kr}) \geq e \quad \forall (0, krj) \in F \tag{17}$$

$$t_{lsm} - t_{krj} + M(1 - g_{kri\_lsm}) + M(2 - h_{kr} - h_{ls}) \geq c_{kri} \quad \forall ((krj, lsm), (lsn, kri)) \in A \tag{18}$$

$$t_{kri} - t_{lsn} + M(g_{kri\_lsm}) + M(2 - h_{kr} - h_{ls}) \geq c_{lsm} \quad \forall ((krj, lsm), (lsn, kri)) \in A \tag{19}$$

$$g_{kri\_lsm} \in \{0, 1\} \quad \forall ((krj, lsm), (lsn, kri)) \in A \tag{20}$$

$$h_{kr} \in \{0, 1\} \quad \forall k \in J, r = 1, ..., R_k \tag{21}$$

$$h_{kr} = h_{k'r} \text{ for job } k \text{ and } k' \text{ which use the same train} \tag{22}$$

$$\sum_{r=1}^{R_k} h_{kr} = 1 \quad \forall k \in J. \tag{23}$$

By solving this MILP, we will obtain the platforming decision, which would result in the minimum *TT*. Additionally, the result will show the time and sequence in which each group of passengers has to go through each area, in order to achieve the minimum *TT* and comply with all the rules. The platform numbers can be announced accordingly.

Case study

Context and assumption

In this research, the case study focuses on London Euston station, which serves as the London-end terminus of the West Coast Main Line. According to the Department for Transport (DfT), during a typical weekday in autumn 2019, the station served an average of 705 train services and accommodated 173,868 passengers (DfT 2019). The London-end of this line includes two tracks (Fast and Slow) for each direction, but there are six tracks to enter/exit the termini from Camden Junction (approximately 2.4km from Euston) with multiple crossings, a flyover and a dive-under to remove conflicts between inbound and outbound trains.

London Euston is recognised as one of the busiest railway termini in the UK. It faces a significant passenger circulation issue that is infamously known as the 'Euston Stampede' (Mirror 2017). Currently, the management of passenger circulation and train platforming decisions are done separately without coordination. With many platforms and mixed types of traffic arriving/departing from the station, the integration of train platforming and passenger flow management poses a complex challenge.

London Euston station is served by three primary train operators: the London Overground (LO), West Midlands Railways (LM), and Avanti West Coast (VT). The LO trains are able to stop at any of the 16 platforms, except platform 1 as it is not connected to their routes. However, they are preferred to stop at platforms 9 and 10 due to the presence of ticket barriers. Similarly, LM trains can physically stop at any platform; however, platforms 5–15 are typically allocated for their use. It should also be noted that, due to train length constraints, LM trains with head codes beginning with 2J, 2K, 2N and 2T cannot stop at platforms 9 and 10. On the other hand, VT trains, with a maximum train length of 265 ms, are physically unable to stop at platforms 8–11. In practice, VT trains generally stop at platforms 1–7 and 12–16. According to the infrastructure manager timetable planning rules (NetworkRail 2021), a minimum headway separation between each arrival and departure train for each platform is 3 min.

Within this study, we selected four one-hour periods from the November 19, 2019 timetable. Our aim was to analyse the busiest periods of the day, specifically the morning peak hour (8:00–9:00) and two evening peak hours (17:00–18:00 and 18:00–19:00). We also included a period of normal operation (14:00–15:00). During these selected periods, there are a total of 56, 52, 50 and 38 trains arriving and departing, respectively.

The simplified layout of London Euston station is shown in Fig. 3. The station is divided into 33 areas. The areas are divided at the location where there is a change in passenger travel direction or at the location where there is a potential of flows merging/intersecting. The dimensions (length l and width w) of each area are given in Table 2 It is assumed that passengers are walking at a constant speed of 1.22 ms per second, based on Fruin's (Fruin 1971) Level of Service C. Table 2 also shows the passing time p needed to pass through each area. It is also assumed that there are 200 passengers travelling on each train service (approximately half of the British Rail Class 390 maximum capacity). The clearing time can then be calculated accordingly. We assume that it takes 90 s for each group of passengers to board/alight a train. According to the passing time calculated in Table 2, it would take approximately 4 min for each group to travel from the concourses to their platform. To avoid passengers being on platforms much earlier than the scheduled departure time, it

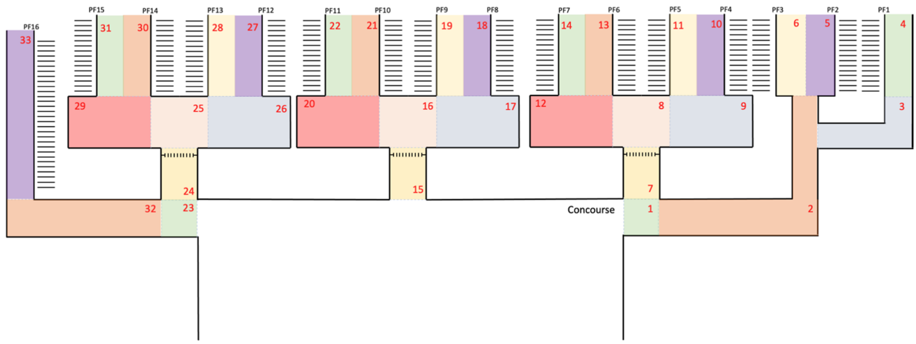

Fig. 3 London euston station simplified layout

Table 2 Dimension and passing time of each area

Area	l (m)	w (m)	p (s)	Area	l (m)	w (m)	p (s)
1	15	7	12	18	60	5.5	49
2	70	7	57	19	60	5.5	49
3	35	7	28	20	20	8	16
4	60	8.5	49	21	60	5.5	49
5	60	11	49	22	60	5.5	49
6	60	11	49	23	15	7	12
7	50	12	40	24	50	12	40
8	20	12	16	25	20	12	16
9	20	8	16	26	20	8	16
10	60	5.5	49	27	60	5.5	49
11	60	5.5	49	28	60	5.5	49
12	20	8	16	29	20	8	16
13	60	5.5	49	30	60	5.5	49
14	60	5.5	49	31	60	5.5	49
15	50	12	40	32	80	7	65
16	20	12	16	33	60	12	49
17	20	8	16				

is established that the platform number announcement can be made 5 min before departure time at the earliest.

Result

As a baseline, we consider the original timetable, in which the platforms are already assigned, eliminating the need for platforming decisions. Thus, the problem at this stage focuses solely on passenger management. To explore alternative scenarios, we compare the original timetable with two additional scenarios. In the first scenario, trains are only allowed to be allocated to *preferred platforms*, while in the second scenario, trains can be allocated to any *physically suitable platform*. These two cases can be formulated as the TPPMP. By allocating trains to different platforms, it would result in different passenger flow manage-

Table 3 Result comparison

	TT (s)			
scenarios	8:00–9:00	14:00–15:00	17:00–18:00	18:00–19:00
Original timetable	78	impasse	604	60
Preferred platforms	28	0	28	0
Physically suitable platforms	0	0	0	0

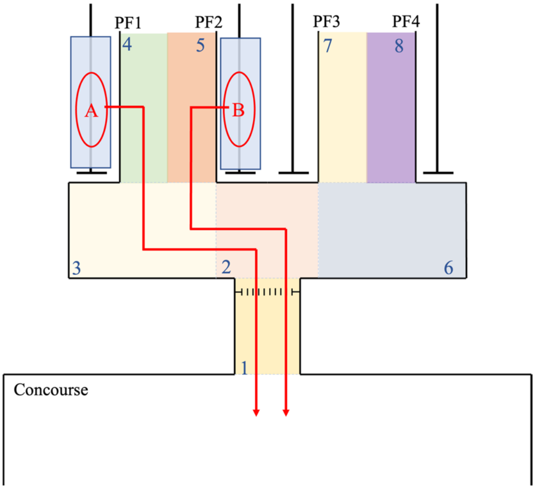

Fig. 4 Unavoidable conflict situation

ment performances. The passenger flow management performance is measured using *TT*, as reported in Table 3.

We use AGLibrary software, developed by Roma Tre University, to solve these TPPMP. The experiments were performed on a MacBook Air (2022) equipped with an Apple M2 processor (8-core CPU, 8/10-core GPU), 24 GB unified memory, and a 256 GB SSD. In each of our case studies, there are approximately 21,000 constraints and 490,000 variables. The average computation time is 4,773 s.

In our previous study (Luangboriboon et al. 2023), we found that according to the original platforming decisions specified in the timetable, there could potentially be conflicts among passengers, where more than one group of passengers are in the same area simultaneously. Specifically, during the 8:00–9:00, 14:00–15:00, 17:00–18:00, and 18:00v19:00 time periods, there were 578 s, 434 s, 498 s, and 209 s of conflict, respectively. To mitigate these conflicts, passenger management actions are required.

By solving the MILP associated with the original platforming decisions, we were able to determine the optimal timing for platform number announcements. With this approach, we are able to avoid conflicts among passengers and adhere to the specified rules. The results show that, with this approach, conflicts among passengers can be avoided during the 8:00–9:00, 17:00–18:00, and 18:00–19:00 time periods. However, it should be noted that this approach still resulted in a significant amount of *TT*, as reported in Table 3

In the 14:00–15:00 case, it was found that it is not possible to manage passenger flow according to the specified rules. This was due to an unavoidable conflict situation. Figure 4 depicted an example of such an unavoidable conflict, where both groups *A* and *B* arrive on nearby platforms simultaneously. As passengers should be able to alight immediately upon arrival, this scenario can lead to conflicts in areas 1, 2, and 3. To mitigate these unavoidable conflict situations, one potential solution is to assign trains to different platforms.

The results presented in Table 3 demonstrate that by reallocating trains to *preferred platforms*, the impasse situation during the 14:00–15:00 time period can be avoided and passenger flow can be effectively managed according to the specified rules while resulting in no *TT*. Similarly, for the 18:00–19:00 case, *TT* can be eliminated by allowing trains to be allocated to *preferred platforms*. In the 8:00–9:00 and 18:00–19:00 cases, although there is still some *TT* incurred by only allowing trains to be allocated to *preferred platforms*, it is significantly reduced compared to the previous scenarios.

Furthermore, by allowing trains to be allocated to any *physically suitable platform*, thus providing more platforming options, the *TT* can be further minimised. The results presented in Table 3 demonstrate that with this approach, the *TT* can be completely eliminated in all four periods under consideration. This indicates that by adopting a more flexible platforming strategy, it is possible to improve passenger flow efficiency and reduce delays.

To visually represent the obtained results, Gantt charts are used to illustrate the passengers' time and sequence information, which were obtained through the solution of the MILP. These charts provide an illustration of the occupation time, including both the passing time and clearing time, for each group of passengers in each area of the station. For the purpose of this example, we will focus on the 8:00-9:00 instance, which involves a total of 56 train services denoted by letters from *A* to *BD*. In particular, we will highlight the services *G*, *O*, and *AQ* to provide a more in-depth analysis of the results.

Based on the current timetable, services *G*, *O*, and *AQ* are scheduled to depart from platforms 13 (area 28), 14 (area 30), and 9 (area 19). To analyse the occupation time of passengers in specific areas, Figs. 5 and 6 illustrate the occupancy of areas 15–22 and 23–33, corresponding to platforms 8–11 and 12–16, respectively. The results indicate that for ser-

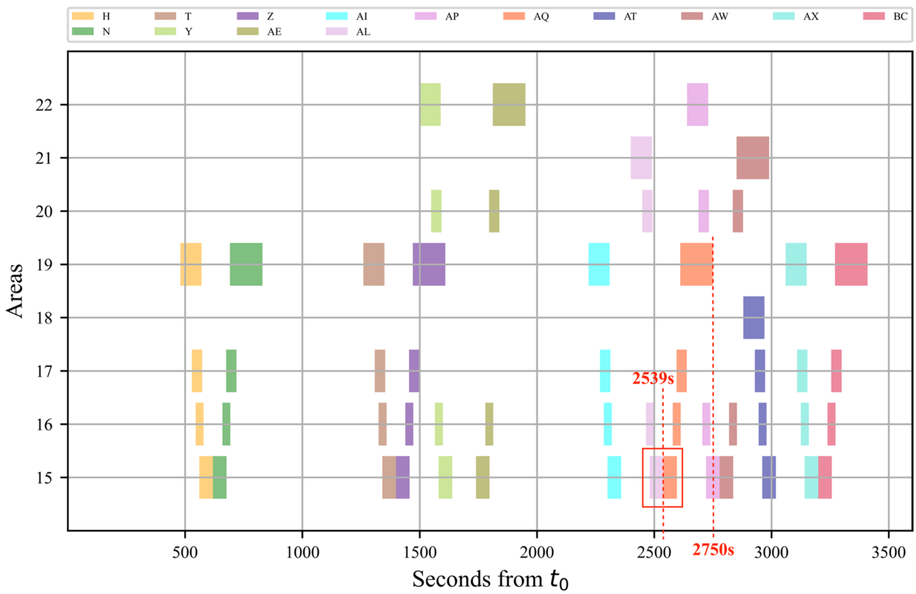

Fig. 5 Area 15–22 Occupation Time for 8:00–9:00 Case with current timetable platforms

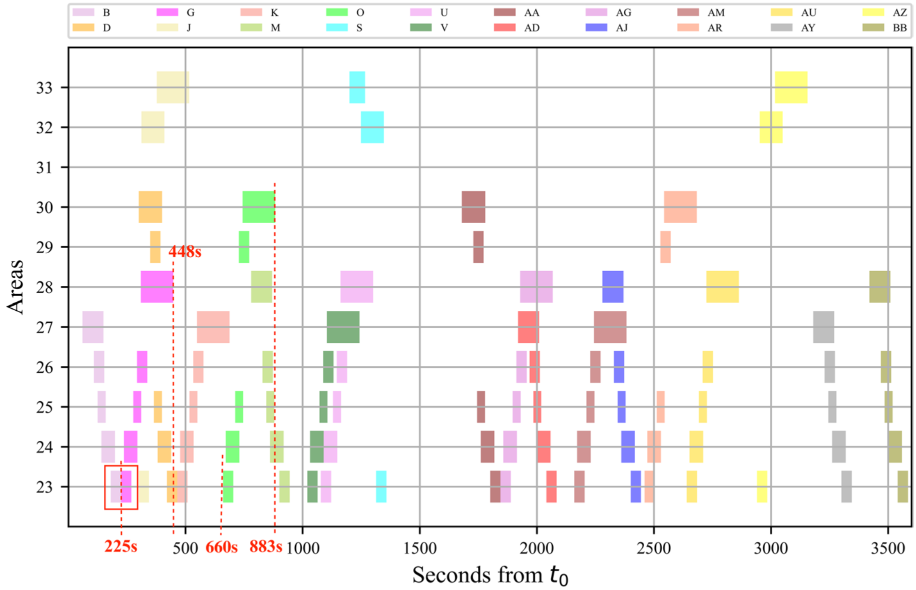

Fig. 6 Area 23–33 Occupation Time for 8:00–9:00 Case with current timetable platforms

vice *AQ*, the platform number should be announced at $t = 2539s$, and consequently passengers would finish boarding at $t = 2750s$, as shown in Fig. 5. This indicates a delay of $50s$ compared to the scheduled departure time of $t = 2700s$. To avoid this delay, passenger group *AQ* would need to proceed earlier. However, this would result in a conflict with group *AL* in area 15, as indicated by the red box in Fig. 5. Similarly, for service *G*, it is suggested that the passengers should be allowed to start proceeding at $t = 225s$ to avoid a conflict with group *B*, as highlighted by the red box in Fig. 6. However, they would finish boarding at the earliest by $t = 448s$, resulting in a delay of $28s$ (the scheduled departure time is $t = 420s$). On the other hand, for service *O*, passengers will start boarding at $t = 660s$ and will be able to finish boarding at $t = 883s$ which is before their scheduled departure time, as shown in Fig. 6. The *TT* in this scenario is 78 s, as reported in Table 3.

In the scenario where trains are allowed to be allocated to the *preferred platforms*, services *G* and *O*, being LM services, are preferred to be assigned to platforms 5-15. Consequently, the optimal solution suggests reassigning service *G* to platform 8 (area 18) instead. This adjustment allows passengers in group *G* to start proceeding earlier, at $t = 160s$, and complete boarding by $t = 331s$, as depicted in Fig. 7. As a result, the previous delay of 28 s for service *G* is avoided. Similarly, for group *AQ*, the reallocation of service *AL* to platform 14 (area 30) enables group *AQ* to proceed earlier, at $t = 2,459s$, and finish boarding at $t = 2,558s$, as shown in Fig. 7. Consequently, the previous delay of 50 s for service *AQ* is eliminated. However, in this particular case, service *O* is also reassigned to platform 6 (area 13), as illustrated in Fig. 8. To prevent conflicts with group *I*, passenger group *O* needs to be held in the concourse for a longer period, resulting in a delay of 28 s. In this case, the *TT* is 28 s, as reported in Table 3.

In the case where trains can be allocated to any *physically suitable platform*, the optimised solution suggests reallocating train *O* to platform 15 (area 31), as shown in Fig. 9.

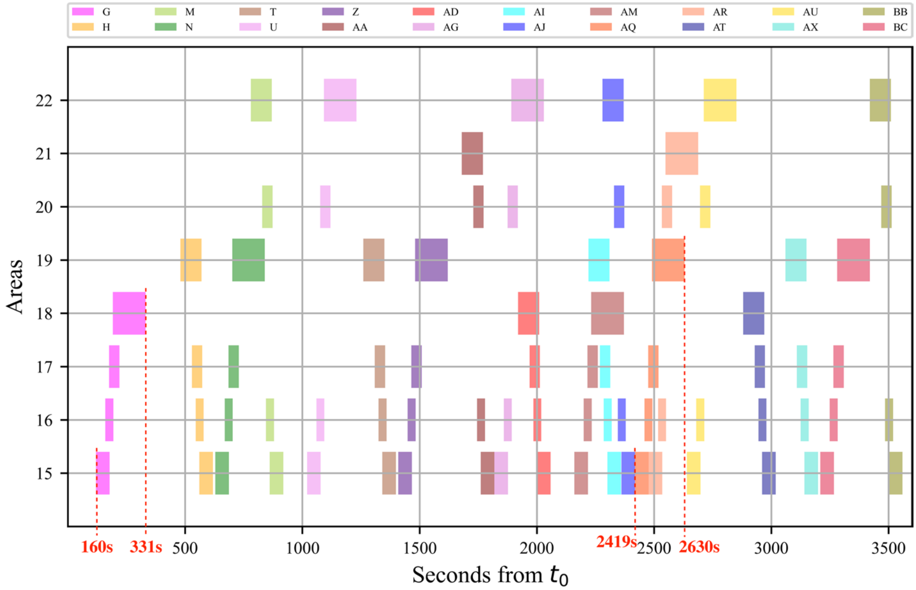

Fig. 7 Area 15–22 Occupation Time for 8:00–9:00 case with *Preferred Platforms*

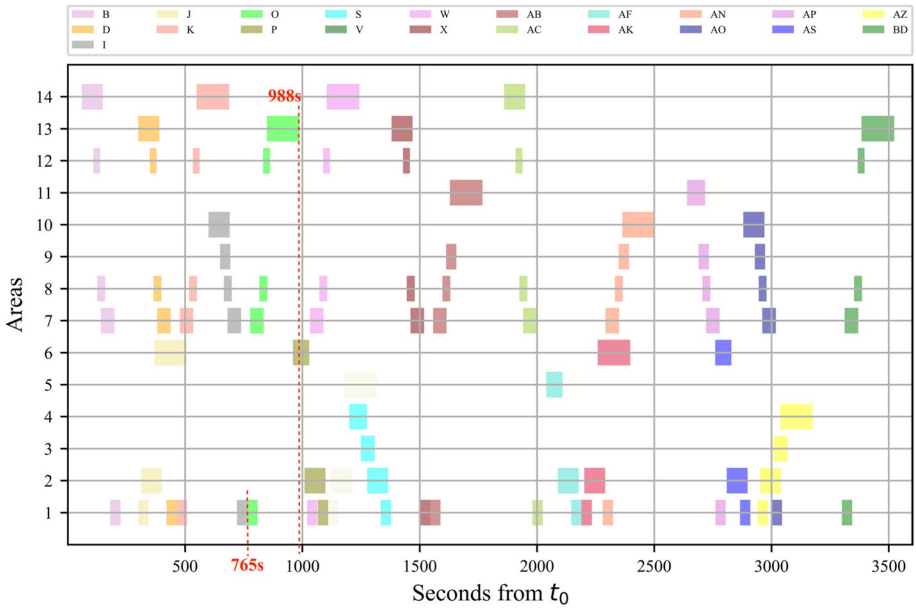

Fig. 8 Area 1–14 Occupation Time for 8:00–9:00 case with *Preferred Platforms*

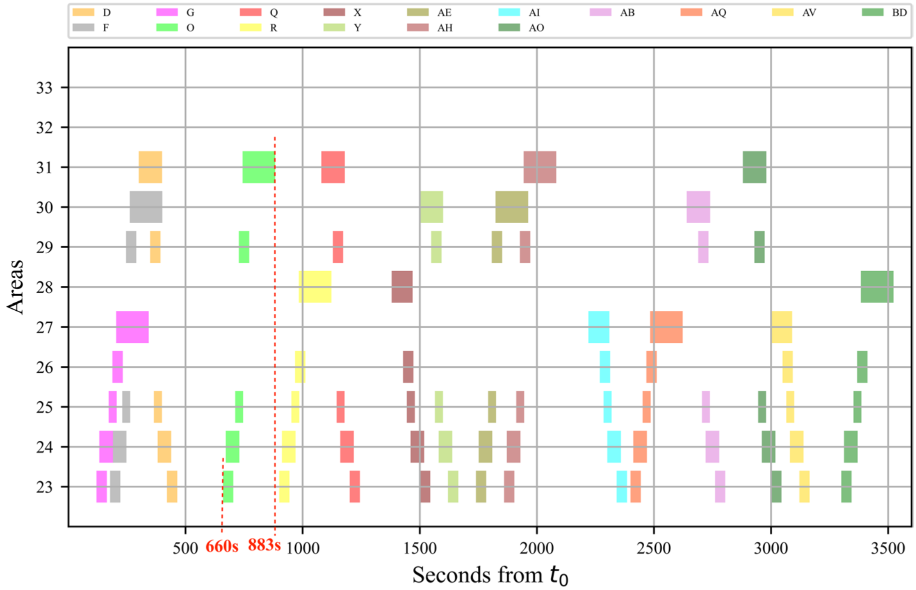

Fig. 9 Area 23–33 Occupation time for 8:00–9:00 case with *Physically Suitable Platforms*

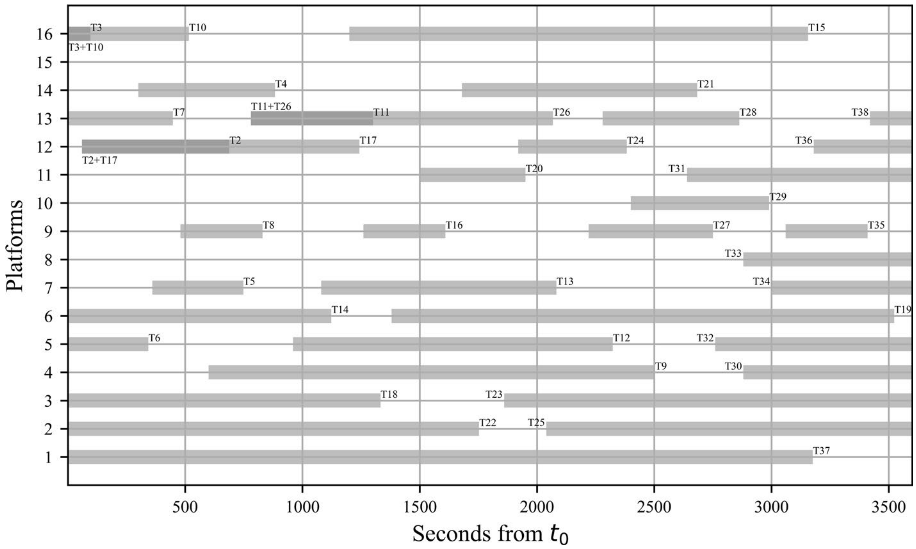

Fig. 10 Platform occupation time for 8:00–9:00 case with current timetable platforms

With this adjustment, group O is able to start proceeding at $t = 660s$ and complete the boarding process by $t = 883s$, resulting in the elimination of delay. The *TT* is therefore reduced to zero in this case, as shown in Table 3.

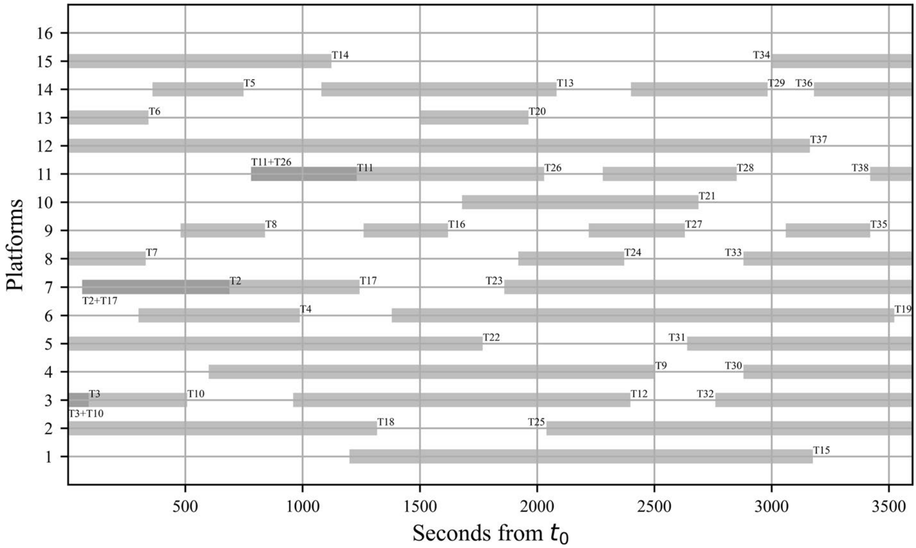

Fig. 11 Platform occupation time for 8:00–9:00 case with *Preferred Platforms*

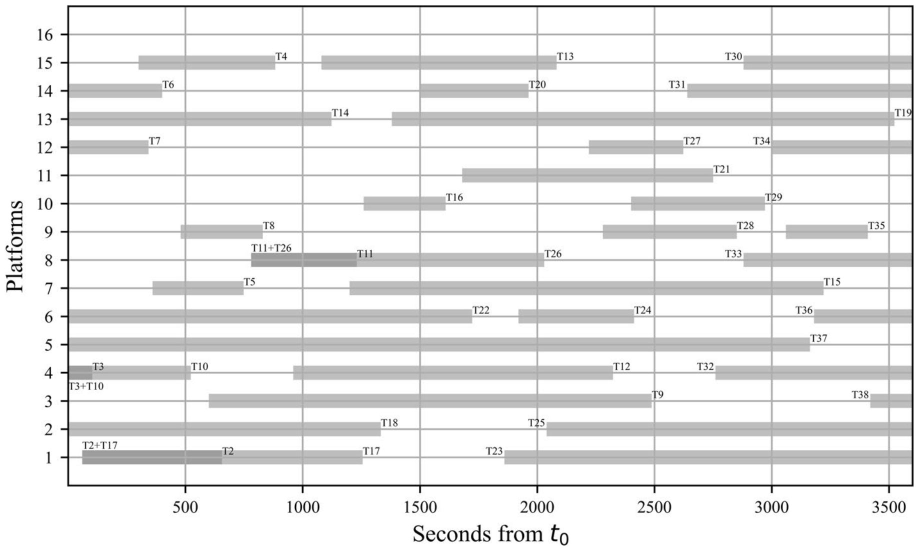

Fig. 12 Platform occupation time for 8:00–9:00 case with *Physically Suitable Platforms*

We also provide Figs. 10, 11 and 12 to illustrate the occupation time of each train at each platform in each scenario. The occupation time represents the duration from when the train arrives at the station until it departs. These figures demonstrate how trains are assigned to different platforms in each scenario while the minimum headway separations between trains are still maintained.

Conclusion and future research

Although extensive research has been conducted on the train platforming problem and passenger management problem, these two aspects have not been integrated within a unified framework. This study proposes a formulation model for the TPPMP that simultaneously incorporates train platforming decisions and passenger flow management. The problem is formulated as a MILP model, inspired by the AG model, and can be solved using a commercial solver. The proposed model aims to support train platforming decisions while optimizing their impact on passenger flow within the station. To evaluate its effectiveness, the model is applied to practical case studies at London Euston station and compared against scenarios using the original timetable, where platforming decisions were predetermined. The results demonstrate that incorporating platform reallocation can significantly enhances passenger flow management efficiency.

Our case study results indicate that, without reassigning trains and without implementing passenger management strategies, significant passenger conflicts can arise within the station area. While managing passenger flow alone can potentially lead to substantial train delays, as reflected as *TT* reported in Table 3. Additionally, in some cases, the original platforming decisions may not even allow for effective passenger flow management according to the specified rules.

However, our analysis suggests that these passenger management issues can be mitigated by reallocating trains to different platforms. Specifically, the case study demonstrates that by allowing trains to be reassigned to other platforms, the amount of *TT* could be significantly reduced or even eliminated, all while maintaining the minimum headway between each train. Furthermore, when trains are allocated to *physically suitable platforms* rather than *preferred platforms*, the *TT* is completely eliminated. Although assigning each platform to a specific type of service (as in the *preferred platforms* scenario) offers benefits such as passenger clarity, our results suggest that a more flexible approach, allowing for platform reallocation, can be highly effective in reducing crowding, particularly during peak times when passenger volumes and train services are at their highest.

While the case study of this research focuses specifically on Euston Station, the proposed tool is applicable to other stations and transport facilities with similar characteristics as well. Future research will explore additional case studies to further evaluate its applicability. Moreover, this study considers only the station area and does not account for conflicts between trains on incoming and outgoing paths. We recommend that future research address these aspects to enhance the model's comprehensiveness.

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