Spatial Layout Planning in Sub-Surface Rail Station Design for Effective Fire Evacuation

Graham Smith and Boris Ceranic

Abstract
Spatial layout planning is an important part of the underground railway station design process, taking into account its need-driven nature and the resulting infrastructure that is sized on demand. The predicted passenger flow rates are the underlining factor and are divided into ‘levels of service’ for space planning considerations. This paper reports on the development of a knowledge-based computer design environment capable of generating multiple spatial layout solutions, thus providing for more effective fire evacuation analysis when compared with the traditional design process. The developed programme, titled SGEvac in this research, utilizes shape grammar theory to provide for automatic generation of solutions at the reference (preliminary) design level, based on visual rules of shape recognition and replacement, their connectivity and spatial relationships. Although it has been developed to meet London Underground Station Planning Standards and Guidelines (SPSG) and related codes of practice, it has both the scope and potential for redevelopment to any other country’s design legislation. Novel shape grammar and functional logic design rules that incorporate station planning design knowledge and guidance are developed and specified, along with the theoretical research. Validation of the results thus far is discussed, with a ‘train on fire in a station’ evacuation scenario analysed.

Keywords – Fire evacuation; layout improvement; shape grammar; station design

INTRODUCTION

Underground stations can broadly be divided into two methods of construction: cut and cover (i.e. excavating a trench and recovering) and tunnelling. The station layout is mostly comprised of the areas that are common to all stations and their spatial planning must be set out with a thorough understanding of passenger circulation patterns. The station components, namely the ticket hall, escalators, concourses, platforms, etc. all interact and connect in a coherent, logical manner with the principal aim of transporting customers to/away from trains as quickly and efficiently as possible. However, achieving this aim must not be detrimental to passenger safety, which is paramount in station design (Smith et al, 2003).

London has the largest, oldest and one of the most complex underground railway systems in the world, dating back to 1863. It has an excellent passenger safety record, with its most notable tragic events taking place at the King’s Cross fire in November 1987 and in the terrorist attacks of July 2005.

The standards and regulations through which London Underground (LU) operates its fire strategies for station design approvals are as follows:

- LU Station Planning Standards and Guidelines (SPSG, 2007)
- Building Regulations (exempt, but still meet functional requirements)
- 1-080: The application of fire safety engineering principles to LU premises
- 1-081: The design and installation of fire protection systems
The figures for predicted passenger flow rates are obtained from Transport for London (TfL). According to TfL 2007 figures, London Underground had over 1 billion passenger journeys for the first time in its history, which is more than the entire national rail network. Thus, the research to improve both the evacuation and normal circulation routes with regard to emergency evacuation (means of escape, travelling distances, position of fire exits, circulation, etc.), could have an important benefit when designing large, interchange stations under major refurbishment or new build consideration.

**THEORY AND APPLICATION OF SHAPE GRAMMAR**


Shape grammar is a method of describing and creating languages of designs where shapes are devices for visual expression. Their composition is controlled by preconceived rules, in a very similar way as to how grammar is used to arrange written words into sentences. The theory provides an approach for the generation of composite shapes based on principles of recognition and replacement of a particular shape. Primitive shapes are transformed and combined to create more complex composites through the application of predefined rules, and so shape language emerges (Cha and Gero, 1999).

Loomis (2003) demonstrates an exercise of a two-dimensional shape grammar with one rule. The shape on the left-hand side is replaced by the shape on the right, which, following recursive application, leads to the generation of simple shape grammar designs, as shown in Figures 1a and 1b, respectively.

As Loomis demonstrates further, it is possible to have the shape rule in Figure 1a applied in four positions (see Figure 2), which would lead to different shape grammar designs. To remove any uncertainty associated with rule application, it is necessary to introduce a deterministic approach where shape grammar rule application is managed by a set of labels. These labels (or rules) constitute a set from which alternative designs are derived. Figure 3 shows some of the possible outcomes that have been derived from the rule set specified in Figure 2.

Tapia (1999) explains how shape grammars, originally defined by hand, ‘naturally lend themselves to computer implementation, [handling] the representation and computation of shapes, rules, grammars and the presentation of alternatives…the designer specifies, explores, develops the language and selects [generated] alternatives’.
Stiny and Gips (1971) define shape grammar as:

\[ S = [VT, VM, R, I] \]  

(1)

where VT is a finite set of shapes; VM is a finite set of labels; R is a finite set of shape rules; and I is an initial shape.

In this research, parameter VT is the finite set of the station infrastructure components shapes and VM is the finite set of labels that comprise the possible station area permutations, mapping two 'legally connected' components into a spatial relation within the overall layout. R is the finite set of the shape connectivity rules, composed of information contained in regulations and guidance documents in terms of the area assignments, adjacency and their connectivity. I is an initial shape (ticket hall in the SGEvac programme).

In summary, a proposed shape grammar system consists of a set of vocabulary elements (station components), a set of rewrite rules and a start state. Station layout can be considered in terms of composite shape generation and its design process in terms of logical sequence and deductive reasoning. It is this approach, based on the function of the building that allows for a transition from 'traditional' layout planning to the computational shape grammar layout generation, that is proposed in this research. However, its application depends directly upon the expert’s knowledge filtered into this rule-based approach.

An additive shape grammar approach (Knight, 1999) is proposed as a suitable technique for generating station layouts. This approach is useful for the irregular station boundaries derived from site specific conditions, where designs are generated from a core (the ticket hall) to which other components are successively added.

Knight (1995) remarks that the rules detailed in Stiny’s Kindergarten paper (1980) can be precisied to externalize a student’s design ideas so that they can be examined, changed and communicated more readily. It is the choice of credible shape grammar alternatives that is important, not the multitude of solutions themselves. Good analytic grammars are both efficient and descriptive, revealing simplicity or regularities behind seemingly complex designs.

**STATION LAYOUT DESIGN CONSIDERATIONS**

Passenger space planning needs to be considered in terms of people’s procedures when they use the Underground. Initially, customers will enter the complex from either street level or via a surface station stairwell. A one- or two-way passage will then take passengers to the unpaid side of the ticket hall where they will purchase a ticket before passing through to the paid side.

Customers then descend using stairs/escalators/ lifts to platform level. At both the top and bottom of stairs and escalators, there is a station component termed the run-off area. The length of the run-off depends on the peak passenger flow capacity of the escalator/stairwell and whether it connects to a platform, passageway or street. It is an area where people move away from the change in level, orientate themselves and make a decision of where to go next (SPSG, 2007).

Generally, at platform level, people will journey to the desired line to take them to their destination via a further passageway or lobby area. Some escalators/ stairs can exit directly onto platforms. The travel process is reversed when alighting from a train and continuing to the surface.

The predicted passenger flow rates and site specific conditions dictate both the number of railway lines and the platform(s) configuration (side, centre or stacked platform). Station composition must also consider areas that are not sized by passenger volume demand, but are required to ensure that the

**FIGURE 3** Labelling shape rule for deterministic grammar designs (Loomis, 2003)
station operates satisfactorily on a daily basis. The station manager’s office, plant and staff rooms, computer rooms, train technician rooms, etc. all need accommodating in the proposed shape grammar formalism. In addition, ancillary accommodation, such as the cleaner’s store, police room, publicity store, retail, etc. also have to be catered for.

To aid designing and sizing infrastructure, levels of service as shown in Figure 4 are used by London Underground. These are based on the work of Fruin (1971) where a detailed study of crowd movement was undertaken. Level A represents free circulation, with subsequent levels growing progressively more restricted in terms of people movement from B to E, culminating with level F that represents a complete breakdown in flow with numerous stoppages.

The approach proposed in this research defines the generic station layout arrangements from the ‘high-level’ spatial site organization to the subsequent, specified components and their logical spatial allocations, as illustrated in Figure 5. The consequent shape grammar rules can then be deduced, taking into account the predicted passenger flow rates, fire safety strategy and relevant design regulations.

**FIRE SAFETY DESIGN STRATEGY**

Before any design commences, a clear identification and appraisal of the key constraints and parameters at the site layout planning stage is required. For example, deep foundations, mains services, archaeological discoveries and even the River Thames will affect station design decisions. Furthermore, structural appraisals, geotechnical surveys, Statutory Undertaker searches, ground contamination testing, environmental impact assessments and land acquisition, etc. all need to be carried out as part of a feasibility study before station layout planning at reference level commences.

**FIGURE 4** London Underground levels of service (SPSG, 2007)
Such constraints may be viewed in a positive context, in terms of services already being provided, helping to justify the business case for a new station. Design procurement strategies may include decisions such as locating toilet areas within x metres of an existing sewer route, or locating electrical plant rooms within y metres of an existing electrical sub-station.

In the real world, parameters such as these constrict layout production and the choice of infrastructure component placement, as opposed to leading to the production of many solutions that are likely to be discarded when, for example, project costs are reviewed. This level of regularity and restriction, typical in station design, is very suitable.
for the application of a prescriptive shape grammar approach.

In parallel with the shape grammar development, functional logic statements are proposed, analogous to the qualitative design review as described in BS 7974: Application of Fire Safety Engineering Principles to the Design of Buildings. The intention is to develop SGEvac procedures in a manner that is recognized by fire safety engineers and designers in practice. The Department for the Environment (DOE) (1996) states that ‘the architectural layout can have a significant influence on people’s movement. Complexity in circulation routes may not be overcome necessarily by signage; these may not have been noticed or they may have been forgotten as a result of stress.’ Hence, station spatial requirements can be reviewed alongside a number of functional logic statements devised in conjunction with the layout planning.

For example, ‘the probability of successful escape through smoke diminishes sharply with (an increase in the) number of decision elements included in the escape path’ (Hesketad, 1999).

A functional logic statement response to the above would be to minimize such decision elements, thus enabling faster egress. Other examples of functional logic statements employed are:

- no corridor or staircase will reduce in width along escape routes
- length of the passages are to be minimized
- maximize level areas to facilitate faster travel speeds for escapees
- maintain uniformity to aid way-finding and relative orientation
- evacuation and normal circulation routes are to be the same
- exits will be prominent, easily identifiable and straightforward to reach.

Such statements are intuitive by their nature and are part of the qualitative reviews in the traditional design process. Due to time constraints, only a limited number of possible alternatives in terms of the spatial layout improvements are ever considered, if any. In contrast, SGEvac offers not only the opportunity to consider a significant number of possible alternatives but also the means of quantitative assessment via fire evacuation simulations.

Garling et al (1983) contend that newcomers to an environment first learn a number of salient locations, then the paths in between and finally organize the acquired knowledge in a spatial system. Indeed, avoiding symmetry and lack of differentiation from the user’s viewpoint is a good practice for station design, considering perception of relative orientation in the station. This is where interaction between the designer and computer program becomes essential; and it is in this context that the research argues the role of SGEvac as a computer-aided design tool, not as a substitute for the designer.

A comparative methodology overview is given in Table 1. The processes of BS 7974, the procurement of a general logic model (Galle and Kovacs, 1992) and the shape grammar development stages are benchmarked against SGEvac procedures. This, perhaps, has most relevance to fire safety engineering, since it is with this objective that the proposed shape grammar system is to be used in practice.

Research studies such as one by Magnusson et al (1995) note that fire safety engineering has motivated designers and regulators to examine alternative code compliance approaches based on a greater reliance upon quantitative analyses. This has led to reassessment of prescriptive approaches and consequent adjustments as required. It is now accepted that existing prescriptive practices should be evaluated by quantitative performance-based methods as a part of the overall fire safety strategy, as encouraged in the Regulatory Reform (Fire Safety) Order (RRFSO) 2005. SGEvac follows this trend, augmenting the array of tools available for performance-based fire safety engineering design.

There is obviously an inevitable need for designer input and control at all stages of the design process. Due to the potential necessity for deviation from standards, via fire safety engineering judgement, the proposed shape grammar approach cannot alone model project-specific concessions.

Still, the movement away from prescription, via BS 7974 and the RRFSO, to risk-based judgement places computer-aided design tools such as SGEvac in a position of interdependency with other design.
criteria: neither can be formulated in isolation. This reinforces the view that computers will in future play an ever-increasing role in aiding and enabling the design teams, but will never be able to replace them.

**SYSTEM DEVELOPMENT**

Figure 6 describes the modular approach proposed for the system development, offering the added potential of dual-purpose application in the design process. It allows the designer to use the system either as a whole or to take advantage of its independent modules. The system offers designers complete control over the shape grammar composition and layout modifications, together with the constant monitoring facilities and ability to discard any solutions deemed to be ‘inferior’.

The proposed system is partitioned into three main modules – ‘expert knowledge’, ‘layout’ and ‘testing’ modules. The expert knowledge module captures the expertise available to facilitate accurate shape grammar generations of layout design. This module provides the designer with the ability to interactively reference Station Planning Standards and Guidelines (and other relevant fire safety regulations), allowing him/her to make necessary site-specific decisions and to control the ‘high level’ shape grammar composition rules.

The designer specifies passenger flow rates and designates the overall site boundary dimensions that define the permissible station footprint. The final exit positions are also stipulated at this stage, with these often being constrained by the existing built environment.

With this data supplied, the shape grammar generations commence in the layout module. The area assignments, adjacency requirements and layout composition rules are defined in detail at this stage. Once the designer has made decisions with regard to the layout composition, the computer becomes the central tool for generating, searching and logically sorting through the permissible permutations of possible layouts. The user has the option to auto-generate layouts (usually for sites without many constraints) or to manually control the layout assembly (a decision normally associated with heavily constrained sites).
The testing module is used to evaluate potentially suitable layouts at reference level by exporting them to AutoCAD via standard drawing data exchange format and analysing them in the context of project-specific site constraints and requirements. A level of drawing detail is then added and the layout solution is exported to Simulex, a building evacuation simulation software package. Once the occupant numbers and person groups are assigned and the escape and vertical circulation routes defined, the simulation software is capable of the accurate measurement of all travelling distances, creation of distance maps and calculation of evacuation times for different fire scenarios (e.g. different group affiliations, persons exiting via different

DDE – Database Data Exchange
DXF – Standard Drawing Data Exchange

FIGURE 6 Proposed SGEvac algorithm
routes and having delayed movement in response to a fire alarm signal). The design team then assesses the results against the qualitative fire safety design goals set earlier to establish whether improvements to evacuation times have been made.

**DETAILED ANALYSIS OF STATION COMPONENTS**

In conjunction with the site boundary, final exit positions and passenger flow specification, consideration must also be given to the vertical site dimension. The shape grammar system assumes all final exits are at ground level, with the ticket hall and platform(s) being the other two elements that require the user to determine their depth relative to the final exits. In so doing, SGEvac selects the correct interchange components by an event-driven mechanism that evaluates the height change and passenger volume demand. Thresholds for both criteria have been defined, as shown in Table 2 and Equations 2–5.

![Table 2](image)

The above constructs also condition the run-off dimensions associated with each of the interchange components (between 4 m and 12 m, as stipulated by SPSG). This being the case, run-offs are used to size the ticket hall length. Figure 7 shows the paid side of the ticket hall, with variable distances shown between the escalator or staircase and the gateline.

The paid side of the ticket hall is always dictated by run-off distance, while the unpaid side is governed by two parameters; the run-off and the concourse area required for the heaviest 15-minute passenger flow. If the maximum 15-minute passenger flow figure multiplied by 1 m² (say, answer A) is larger in plan area than the product of the gateline width multiplied by the relevant run-off (say, answer B), then answer A will be incorporated into the layout. The reverse is true if B is the greater number. This ensures that the station is always sized appropriately.

Figure 8 shows a ticket hall layout, with the gateline dictating the width (denoted as Tick_H_wd), itself conditioned by the passenger flow figures, calculated as shown in Table 3. The table only evaluates entry flow requirements, but SGEvac will repeat the same process for exit gates to produce a correctly sized gateline.

In this case, the maximum 15-minute passenger flow capacity size prevailed over the run-off to create the unpaid side overall.

The divide between the paid and unpaid side of the ticket hall is the sized according to Table 4. SGEvac shape rules mandate that entry gates are always located adjacent to the ticket office queuing space (designated as Q_TIW) to avoid conflicting passenger entry and exit flows. The LU standard is to
FIGURE 7 Passenger flow rate run-off requirements (SPSG, 2007)

FIGURE 8 SGEvac ticket hall arrangement
allow for 4 m (or a five-person queue), as shown in Figure 8. The overall gateline is defined by summing both exit and entry gate numbers obtained from user-inputted passenger figures.

The length of the ticket office interface with the ticket hall is stipulated by the number of ticket issuing windows (TIWs), plus excess fare windows (EFWs). TIWs always belong on the unpaid side of the ticket hall and EFWs always on the paid side, both for revenue protection reasons. This situation facilitates a precise shape grammar labelling for the ticket office to ticket hall/queue space connection.

Passenger operated machine (POM) enclosures are normally connected to the ticket hall, ticket office and its own queue space (noted as Q_space in Figure 8).

To make shape rule specification manageable, all station areas are divided into groups, arranged to suit the most probable connection patterns in the station. Table 5 shows the group station manager’s office example, with all other station components following the same concept.

London Underground views its stations as large basements (Weller, 2007) and escape distances from platforms are based on agreed dispensations with the London Fire Brigade. SGEvac respects these distances by placing restrictive labels on the platform so that they cannot be exceeded, as demonstrated by the example shown in Figure 9.

SGEvac escape stair infrastructure may be positioned up to 20 m from the end of platforms, to avoid undesirable ‘dead end’ conditions. The 45 m maximum platform travel distance starts from the nearside junction of the two 3.3 m wide escape staircases, with the 45 m distance rule creating a shortfall in the platform centre of 3.4 m. Generally, locating three interchange components (e.g. stairs

### TABLE 3 Gateline width calculation

<table>
<thead>
<tr>
<th>METHOD</th>
<th>WORKED EXAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obtain peak hourly flow rate through ticket hall</td>
<td>Say, 6500 people/hr</td>
</tr>
<tr>
<td>Calculate 5-minute peak passenger flow</td>
<td>6500/12 = 541</td>
</tr>
<tr>
<td>Allowance for ticket rejection</td>
<td>541 + 20 = 561</td>
</tr>
<tr>
<td>Allowance for growth in use demand</td>
<td>561 x 110% = 617</td>
</tr>
<tr>
<td>Assume 125 people use each gate over the 5-minute peak passenger flow period</td>
<td>617/125 = 4.93</td>
</tr>
<tr>
<td>Round up gates to nearest whole number</td>
<td>5 gates required</td>
</tr>
</tbody>
</table>

### TABLE 4 London Underground ticket hall gateline parameters/regulations (SPSG, 2007)

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>DIMENSIONS (W X D)</th>
<th>POSITION/ARRANGEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined manual/equipment gate</td>
<td>1750 x 270 mm. Height – 1300 mm.</td>
<td>Adjacent to ticket office. Can include luggage facility</td>
</tr>
<tr>
<td></td>
<td>1400 mm clear opening</td>
<td></td>
</tr>
<tr>
<td>Manual gate – passenger</td>
<td>1750 x 270 mm. Height – 1300 mm.</td>
<td>Adjacent to ticket office. With more than 6 walkways in a single gateline or significant interchange with mainline stations, airport or tourist traffic, provide separate luggage chutes</td>
</tr>
<tr>
<td>gate/luggage port</td>
<td>900 mm – clearance and outward opening</td>
<td></td>
</tr>
<tr>
<td>Manual gate – single leaf</td>
<td>1394 mm. Height – 1300 mm.</td>
<td>Beside the dedicated excess gates</td>
</tr>
<tr>
<td>with luggage port</td>
<td>69.5 mm clearance</td>
<td></td>
</tr>
<tr>
<td>Gateline attendance report</td>
<td>990 x 1240 mm</td>
<td>Within the controlled zone, but not necessarily part of the gateline. Usually close</td>
</tr>
<tr>
<td>Station control unit (SCU)</td>
<td>432 x 430 mm</td>
<td>Should be installed within a secure enclosure (which could be a ticket office) and also with a clear view of the gates. Controls and monitors the station underground ticketing system equipment</td>
</tr>
<tr>
<td>Manual emergency exit gates</td>
<td>1900 x 125 mm</td>
<td>Adjacent to ticket office. Add these gates rather than adding extra UTS gates for evacuation purposes</td>
</tr>
</tbody>
</table>
or escalators) at these distances will result in compliance with the Underground standards, but it may not always be possible (or practical for an interchange situation) to procure such a layout.

Lengths of station components are controlled by a range of criteria. For the platform, it is the length of the train vehicle; for interchange components, it is the vertical height in the terms of the depth to the platform level; for passages, it is the designated final exit positions and the existing station areas already generated.

Vector direction labels are underpinned by the permissible union of compatible spaces: two points of contact will be maintained so as not to restrict the width of connecting passenger areas. This undue constriction of passenger flow at the head of a passage also satisfies realistic construction practice. Non-passenger and ancillary area vector directions are as per project requirements and the successive area additions managed by the SGEvac rule groupings.

To create alternative layouts, SGEvac uses a 'randomize' rule. In this shape grammar rule, initial state infrastructure is generated as per guidelines, but it can randomly change the location of component arrangements within the predefined boundaries so that a number of possible alternative layouts are produced. The designs can then be interrogated and ranked by their travelling distances and against the qualitative functional logic statements.

The SGEvac design tool developed in this research is based on a highly restrictive additive grammar rule set, due to SPSG’s prescriptive guidance and the nature of the layout planning problem. As Grimsdale and Chang (1996) argue, many published grammars lack high-level reasoning during the iteration process since they are often concerned with the development of shape grammar theories, rather than their practical applications. By contrast, SGEvac, being a practical application, has a complete set of primitive shapes only possible to arrange in a certain way. It thus provides viable reference design layout compositions, based on SPSG, with further interventions possible by the designer.

**SYSTEM DEVELOPMENT TO DATE**

The SGEvac prototype is compiled within the C# language environment, allowing for modular object-oriented programming (suitable for shape grammar). Figure 10 shows the main interface, where the station name and relevant LU fare zone are entered (which impacts on sizing infrastructure), as are the ticket hall and platform depths, the overall site boundaries and final exits’ positions. The peak passenger flow figures, over the relevant time interval of normally 3 hours, are also specified. SGEvac is then capable of accurately calculating all passenger area infrastructure based on the SPSG guidelines, as already discussed.
The history of auto-generated layouts is accessible from this screen and the user is given the capability to delete and copy them (useful when minor alterations are required to produce an alternative layout).

Shape labelling in the programme is multi-faceted, which is necessary since many station components have various possible connections. An escalator, for example, may connect to a passage, travelator, ramp, escalator run-off, stair run-off, lift or the ticket hall, so all such connections need adding to the component properties. The SGEvac grouping of component interactions is accessed from menu toolbars that allow insertion of legislative compliant station area connections, as shown in Figure 11.

Once the position and the depth of the ticket hall and platform are specified, the railway track is inserted dependent on the platform configuration. The platform is the only possible connection to the track, but the track can be positioned either side of platforms so that a side or centre (island) platform layout is possible.

Non-passenger and ancillary areas are also selectable from the shape grammar library via property windows for each station component, e.g. the ticket office properties window as shown in Figure 12.

Figure 13 shows examples of the layout module station components available in the SGEvac programme.

Figure 14 shows the layout module interface. Information on the components (relative position in the overall site layout and its absolute sizing) is displayed at the bottom of the screen once the component is selected from the list. In addition, a measurement bar (in metres) at the base of the interactive design environment provides a sense of scale for the designer.

A checklist summarizes the station areas included in the layout, but a more detailed analysis is possible via a report function if required. In addition to this detailed list, a summary screen, accessed from the main interface collates all specified components in each generated layout. This screen lists all passenger, non-passenger and ancillary areas in their respective categories, with infrastructure width data of passenger areas also summarized. It also has an evacuation summary, where the train frequency is
specified and the train evacuation load (taken as peak 'rush hour' loading) is displayed. This section of the summary screen is useful for input into Simulex where fire evacuation test runs of the building layout can be implemented.

The 'show hierarchy' function in Figure 15 allows design team members to view the progression of designs by superimposing connecting lines between station elements in the order of their composition. This also serves as a safeguard against deleting
components out of sequence that could lead to an invalid solution.

Once auto-generated layouts are complete with correctly sized and legitimately connected station components, manual insertion of non-passenger areas would then commence. Upon completion, the generated layout is transferred to AutoCAD via dxf file format, as shown in Figure 16. Once in AutoCAD, the layout has a level of detail added by the designer such as door openings, passage connections, fire escape openings, etc., so that passenger flows may be assessed. It is then exported to Simulex for fire evacuation simulation analysis, again via dxf file format.

Simulex understands any voids as potential circulation routes, treating the rest as solid and permanent obstructions, i.e. walls, internal structural elements, permanent fixtures, etc. Since its solution operates in a two-dimensional environment for what in effect is a three-dimensional problem, the means of vertical circulation (e.g. staircases) have to be established. True lengths of staircases must be specified, based on the total length of all flights (sloping length) and the intermediate rests. The fire exits need to be defined, both in terms of their location and width. The links have to be established to define the point of the connection between the floors and staircases/escalators/ramps. The travelling distance maps are then calculated, type and number of occupants specified, building populated and the evacuation simulation performed.

**SYSTEM TESTING AND VALIDATION**

Kuligowski and Peacock (2005) define and recommend the following ways of validating evacuation models:

- validation against code requirements
- validation against fire drills or other people's movement experiments/trials
FIGURE 14 Layout module graphical user interface

FIGURE 15 SGEvac hierarchy function
validated against literature on past evacuation experiments. Component testing is regarded as testing computer code that drives the model, checking for elementary errors. Functional validation involves checking that the model possesses the ability to exhibit the range of capabilities required to perform the desired simulations. Component testing and functional validation for SGEvac is carried out against code requirements insofar that all calculations for infrastructure sizing are evaluated manually so that the method and answer are known to be correct. It uses the Simulex program to aid the modelling of people movement and to test the hypothesis of improvement to evacuation times, thus relying on Simulex’s own rigorous validation process. Simulex has been used extensively in practice as well as a validating model for other evacuation softwares (Kuligowski and Peacock, 2005). SGEvac has gone through its initial completion and validation process, with final validation proposed for the end of the year.

Furthermore, Galea (1999) deconstructs the validation process into four main areas – component testing, functional testing, qualitative validation and quantitative validation. This approach is more suitable for models such as SGEvac than for those based on compliance with code requirements and hence it is the one adopted for the validation in this research.

Component testing is regarded as testing computer code that drives the model, checking for elementary errors. Functional validation involves checking that the model possesses the ability to exhibit the range of capabilities required to perform the desired simulations. Component testing and functional validation for SGEvac is carried out against code requirements insofar that all calculations for infrastructure sizing are evaluated manually so that the method and answer are known to be correct. It uses the Simulex program to aid the modelling of people movement and to test the hypothesis of improvement to evacuation times, thus relying on Simulex’s own rigorous validation process. Simulex has been used extensively in practice as well as a validating model for other evacuation softwares (Kuligowski and Peacock, 2005). SGEvac has gone through its initial completion and validation process, with final validation proposed for the end of the year.
FIRE EVACUATION SIMULATION RESULTS

The considered ‘train on fire in station’ scenario takes into account the service interval of 3.33 minutes (based on 18 trains per hour), the crush capacity of a four-car train together with the number of people waiting on the platform after cancellation of one service (i.e. after 6.66 minutes). On the opposite platform, the evacuation load is taken to be the normal boarding/alighting load assuming no cancellations to services (50% of all boarders and alighters).

Evacuation load predictions were based on TfL 2006 projected passenger flows, with an average flow of 36 people/minute for boarders and 123 people/minute for boarders and alighters combined. The train crush capacity was averaged at 165 people/car. The simulation also models evacuation from the ticket hall level to assess the impact of dispersing crowds at peak times in this part of the station. From these figures, the total evacuation load was calculated as follows:

Platform 1
Boarders \((36 \times 6.66 \text{ min})\) = 240
Train crush load \((165 \times 4)\) = 660

Platform 2
Boarders and alighters \((123 \times 0.5 \times 3.33 \text{ min})\) = 205
Ticket hall = 470
Total station evacuation load = 1575 people

The simulation results have been captured as images at 25, 50, 100 and 300 second intervals, respectively, for both platform and ticket hall levels, as shown in Figures 17 to 20.

The provided means of escape follow LU SPSG4 requirements insofar that the maximum travelling distance on a platform to an exit is no more than 45 m (i.e. exits must be no more than 90 m apart) and that the dead-end travelling distance is no more than 20 m to an exit. Hence, each platform is provided with three exits. The MIPs’ (mobility impaired persons) means of escape is provided from both ends of platforms via emergency evacuation lifts. Total evacuation time (i.e. all people reaching an exit on ticket hall/ground level) was 5 minutes and 24 seconds, with the platform and train load cleared within 3 minutes and 5 seconds. This is within the requirements to evacuate the platform and train load within 4 minutes, with all people reaching a fire-separated route within 6 minutes (the ticket hall is not classed as a fire-separated route).

The performed simulation was based on the minimum travelling distance maps, resulting in each person exiting via the nearest fire exit route. The average 10 second ‘time to start to move’ was assigned to all occupants in order to accommodate for real world people behaviour commonly reported by fire evacuation research studies. The boarders on the end of both platforms (including most people from end carriages of the train) evacuated via staircases/MIP lifts directly to the ground level point of escape. The boarders situated around the middle of platforms together with the people from the two middle carriages used the central escalators to reach ticket hall fire exits. Additionally, some people from the end carriages and some staff/retail unit customers used this route as means of escape.

In this ‘train on fire in station’ scenario, it was assumed that none of the escapes routes are unavailable due to maintenance. However, further evacuation studies will investigate possible scenarios where one of the escalator routes may be unavailable due to maintenance reasons.

FUTURE RESEARCH

Intended future work will concentrate on the further conditioning, developing and modelling of shape grammar design rules, based on the outcomes of the final system validation and LU experts’ feedback. Further research is proposed on the development of a novel layout optimization approach based on the shape grammar rules to investigate the evacuation-related parametric improvements in subsurface/surface railway station design (e.g. minimizing travelling distances).

The fire safety strategy in terms of performance-based fire risk design is an important aspirational aspect of SGEvac, requiring further research and liaison with experts to determine how such varied criteria could be allied with layout planning. This is particularly important where deviation from standards occurs. Thus, further development of the expert
Spatial Layout Planning in Sub-Surface Rail Station Design for Effective Fire Evacuation

FIGURE 17 Station evacuation after 25 seconds

FIGURE 18 Station evacuation after 50 seconds
FIGURE 19 Station evacuation after 100 seconds

FIGURE 20 Station evacuation after 300 seconds
knowledge database would be required, particularly in the light of frequent changes to legislation.

On a more practical note, it could be beneficial to develop the system on a stand-alone modular basis, linked to each generated station component. A list of fire safety strategy objectives and functional logic statements can then be specified for commonly recurring items (such as emergency lighting, fire alarm detectors, sprinkler heads, etc.) and spaced according to the designer’s wishes or via shape rule formulation.

Site constraint issues would also benefit from future development, as well as a move towards development of the 3D shape grammar version. Once devised, other relevant 3D modelling systems, such as computational fluid dynamics (CFD) smoke movement software could be utilized in conjunction with SGEvac.

CONCLUSIONS
The computer-aided modelling environment under development is intended to act as a layout planning aid for those who practice in sub-surface/surface railway station design. The system under development carefully considers London Underground Station Planning Standards and Guidelines, together with other relevant fire safety regulations that influence overall fire strategy design. The proposed computer-aided design environment (SGEvac) is based on highly restrictive additive shape grammar rules, driven by a kernel of key passenger flow information to generate station plan solutions.

The major benefit to the design team is the ability to review multiple layouts of accurately sized and correctly placed infrastructure at the reference or preliminary stage of the station layout planning design process. Time is hence saved regarding different option appraisals and quantitative testing using evacuation software should lead to a choice of more effective layouts in relation to means of escape, travelling distances and improvement in the total evacuation times. Modifications to layouts should be straightforward and there is scope to efficiently assess travelling distances and evacuation times for each of the considered alternatives compared with a ‘traditional’ approach.

The proposed novel shape grammar approach is most suited to new-build stations or large refurbishment projects where more design flexibility exists. Sites with many site-specific constraints have

an array of predetermined parameters and will most likely benefit from the manual operation of SGEvac.

Use in other rail systems, due to recurring infrastructure components and inherent functional logic related to the laying out of the station components is also feasible, provided that shape connections and shape rules are corrected to reflect that country’s legislative requirements.

The potential for station layout improvements with regard to emergency evacuation is an area that merits research, especially in scenarios that concern the safety of the general public and form a vital part of London’s transportation system. Potential layout improvements could not only benefit evacuation situations, but also enhance the through-flow of people during peak travelling periods.

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AUTHOR CONTACT DETAILS
Graham Smith (corresponding author): Senior Architectural Technologist, Jacobs (UK) Ltd, Cardinal Square, North Point, 10 Nottingham Road, Derby, DE1 3OT. UK. Tel: +44 (0)1332 234482, fax: +44 (0)1332 344558, e-mail: graham.p.smith@jacobs.com

Boris Ceranic: Programme Leader for BSc/BA (Hons) Architectural Programmes, Room Number 105, Faculty of Arts, Design and Technology, University of Derby, Markeaton Street, Derby, DE22 3AW, UK. Tel: +44 (0)1332 593136, e-mail: b.ceranic@derby.ac.uk

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