SHAPE GRAMMAR SPATIAL LAYOUT PLANNING – THEORETICAL FRAME WORK AND PRACTICAL IMPLEMENTATION FOR IMPROVING EVACUATION TIMES IN SUBSURFACE / SURFACE RAIL STATION DESIGN

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ABSTRACT

The London Underground network is a crucial part of the transportation system in one of only four 'Alpha' world cities. The other three – Paris, New York and Tokyo – also have such sub-surface railway transport systems that may benefit from this shape grammar station design process in a future research proposal.
In London's case, the passenger flow rates are the underlining factor in sizing infrastructure where passengers have access – it is therefore this criterion that provides the basis for the shape grammar formulation for the largest, oldest and one of the most complex underground systems in the world.
The research aims to improve passenger fire evacuation times, with due cognisance of the growth of numbers using the system, and its present susceptibility to terrorist attacks taken into account. The proposed shape grammar approach will provide for generation of spatial layouts, based upon visual rules of shape recognition, replacement / union, their connectivity and spatial relationships.
The paper concentrates on definition and implementation of novel shape grammar design rules that incorporate station planning design knowledge, and in particular also discusses designers' fire risk assessment approach and related knowledge that is also needed to produce credible station design solutions.
Development, to date, of the proposed artificially intelligent CAD environment is also described along with parallel theoretical research. The proposed CAD interface provides familiarity to the designer and avoids incompatibility issues regarding drawing exchange format between various software systems. The shape grammar layouts produced will be tested in SIMULEX, a commercially available evacuation package, and be compared against 'traditionally' designed layouts to demonstrate improvements of preliminary 'reference' designs, which follow the standard London Underground design process as a later stage of this research.

KEYWORDS

Layout improvement, underground station design, evacuation, shape grammar.

INTRODUCTION

The Underground has an excellent passenger safety record - most fatalities on the network are suicides - and the main fire load is the passengers that use the system. Smoking has been banned since the well-documented fire at King's Cross Station in November 1987, and relatively few accidents occur on platforms due to overcrowding at peak times. Such situations are constantly monitored and managed by staff, with Camden Town Station designated as exit-only on Sunday afternoons for this reason.
Concerning future investment, the UK government has promised £16 billion of funding until 2030, with a station proposed for the new Wembley Stadium and works are scheduled to provide transport for the 2012 Olympic and Paralympic Games.

The shape grammar approach is unlikely to have a major impact on this existing built environment in Central London due to many site specific constraints and large numbers of existing interchanges between stations creating an array of pre-determined parameters.
Large refurbishments to existing stations may benefit from the SGEvac software, but its major benefit is with new-build stations where more design flexibility exists for alternative layouts to be generated for the designer's perusal.
Shape grammars are defined over a set of shapes (such as station areas) and are mapped into more complex composites (such as the station itself). The mechanism for arriving at whole station solutions is the use of labels that act as markers. These markers define the permissible connections allowed within station design Standards and guidance; and the adjacency (or width) of such connections, in passenger areas at least, are given by site specific passenger flow rate figures obtained from Transport for London (TfL). Non-passenger spaces and ancillary station units are sized by regulations and are only included in designs via project brief requirements.

OVERVIEW OF SGEvac PROGRAM

The proposed novel system algorithm is graphically represented in Figure 1 below:

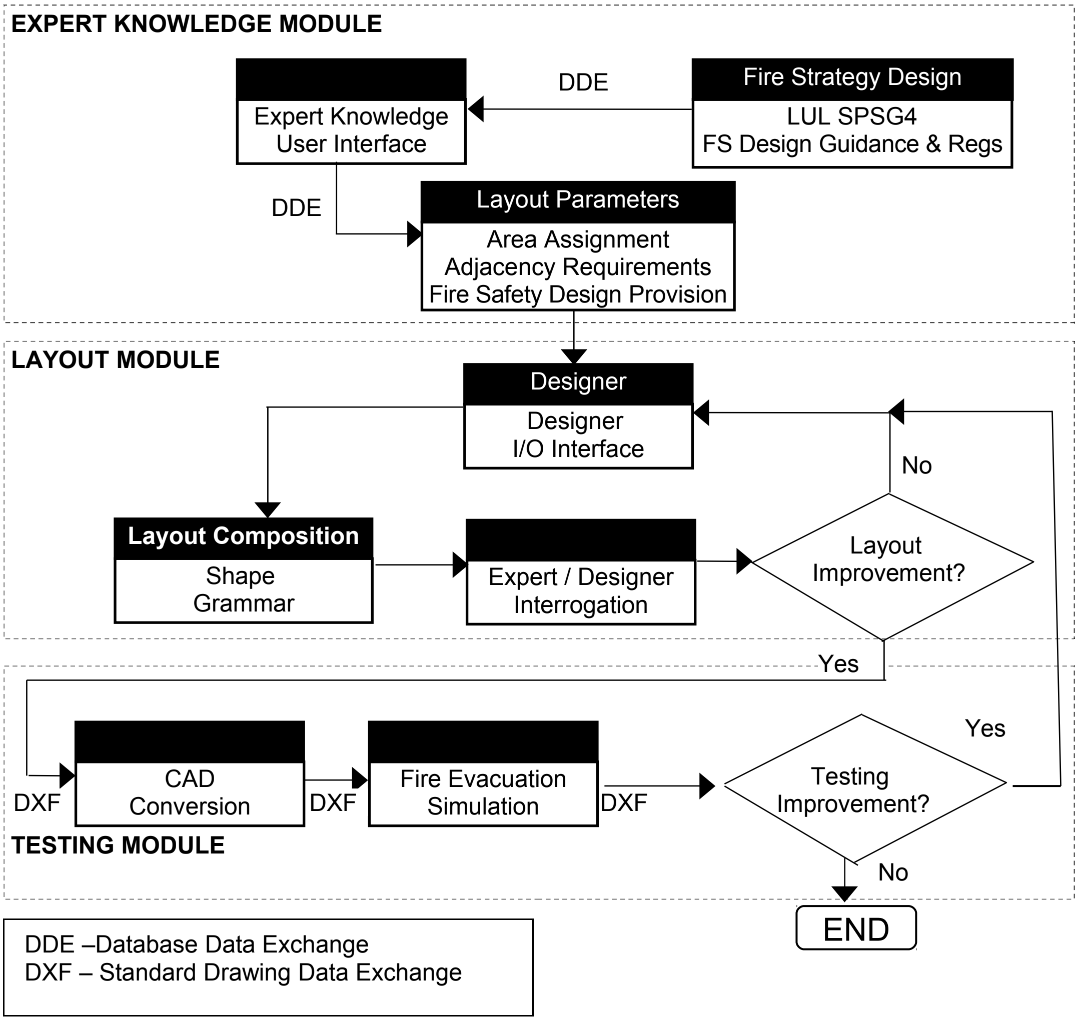


Figure 1 – Proposed SGEvac System Algorithm

The ‘Expert Knowledge’ Module principally incorporates the Station Planning and Guidelines (version 4) and other sections of engineering Standards used by Underground station designers. These are then assessed by the designer with regard to the project brief and site constraints that have been deduced from a feasibility study before layout planning would begin. Onerous site constraints, like at central City station locations, will constrict layout production (as stated in the introduction), but such elements require input into the AutoCAD before the SGEvac program is initiated so that legitimate designs are formed.

Once the program is started, the flow rates may be inputted to define the size of infrastructure in the ‘Layout’ Module. When such passenger flow figures have been specified, the infrastructure can be sized and subsequently stored in the ‘vocabulary library’ in the SGEvac system. With all pre-determined data (feasibility study outcomes and flow rates) set up in the program, the shape grammar generations commence, as described later in this paper. The designer chooses the number of alternatives that are to be generated so that combinatorial explosion of solution states is avoided.

The ‘Testing’ Module is used to evaluate the designer’s intuitively preferred layout(s) by running it / them through the SIMULEX fire evacuation software package. Different scenarios of passenger behaviour can be simulated in SIMULEX so that various realistic situations are analysed – i.e. group affiliation characteristics, persons exiting via point of entry (not necessarily the shortest route).

CONCERNING LOGICAL DESIGN

Station design is best viewed in terms of logic to derive suitable solution states. The project brief can be viewed in a logical context with a number of *policy logic statements* devised and listed alongside the design commentary or description grammar of SGEvac. For example, ‘the probability of successful escape through smoke diminishes sharply with the number of decision elements included in the escape path’ (Hesketad, 1999).

So a *policy logic statement* for a given project brief is to minimise such decision elements to enable faster egress. Furthermore, repositioning entrances relative to the position of train exits for people alighting / departing trains could enhance continuity of passenger flow and reduce evacuation times.

Such statements are intuitive and would be subject to testing via SIMULEX, but before any design is started, a clear understanding of the key constraints and parameters is central to establishing a base diagram (whether using a shape grammar approach or not).

Examples of other *policy logic statements* could be:

- No corridor or staircase will reduce in width along the escape route;
- No long passages or potential hiding places shall be included in the design;
- Maximise level areas to ensure faster travel speeds for escapees;
- Provide continuous markings to aid identifying escape routes;
- Maintain uniformity in architecture to aid way-finding and relative orientation;
- Evacuation and normal circulation routes to be the same;
- Exits to be prominent, easily identifiable and straightforward to reach.

Garling (1983) contends that it is assumed that newcomers to an environment first learn a number of salient locations, then learn the paths inbetween, and finally organise the acquired knowledge spatially in a system. Organisational clarity is indeed essential for station designs.

SYSTEM DEVELOPMENT TO DATE

Figures 2 and 3 below are part of the 'Expert Knowledge' Module section of the SGEvac system shown in figure 1 of this paper. The parameters of the Station Planning Standards and Guidelines are incorporated into the layout generation sub-routines of the proposed software in this module, where the graphical user interface (GUI) provides the designer with interactive control over such parameters and flow figure data and their impact on sizing station components with respect to such design guidance for site specific situations.

Figure 2 shows the first SGEvac interface that will be presented to the designer when the program is summoned. The station name and relevant LUL fare zone is entered by the user, as well as important station flow figures for peak travel times over the relevant time interval. This flow data is used to size all passenger used infrastructure in the station, where figure 3 shows the screen whereby such components may be accessed individually for the designer to choose which components are required, based on the requirements of the project brief.
For example, passages may be 1- or 2-way directional, with each one having a different flow rate (50 people per minute per metre width for single direction, and 40 passengers/min/m width for bi-direction traffic). Once this has been specified by the designer the correct corridor width will be created and stored in the shape grammar library of shapes for any particular scheme for use in the layout generation process. Non-passenger and ancillary areas, designated as required in the project brief, are also stored in this library for each station scenario.

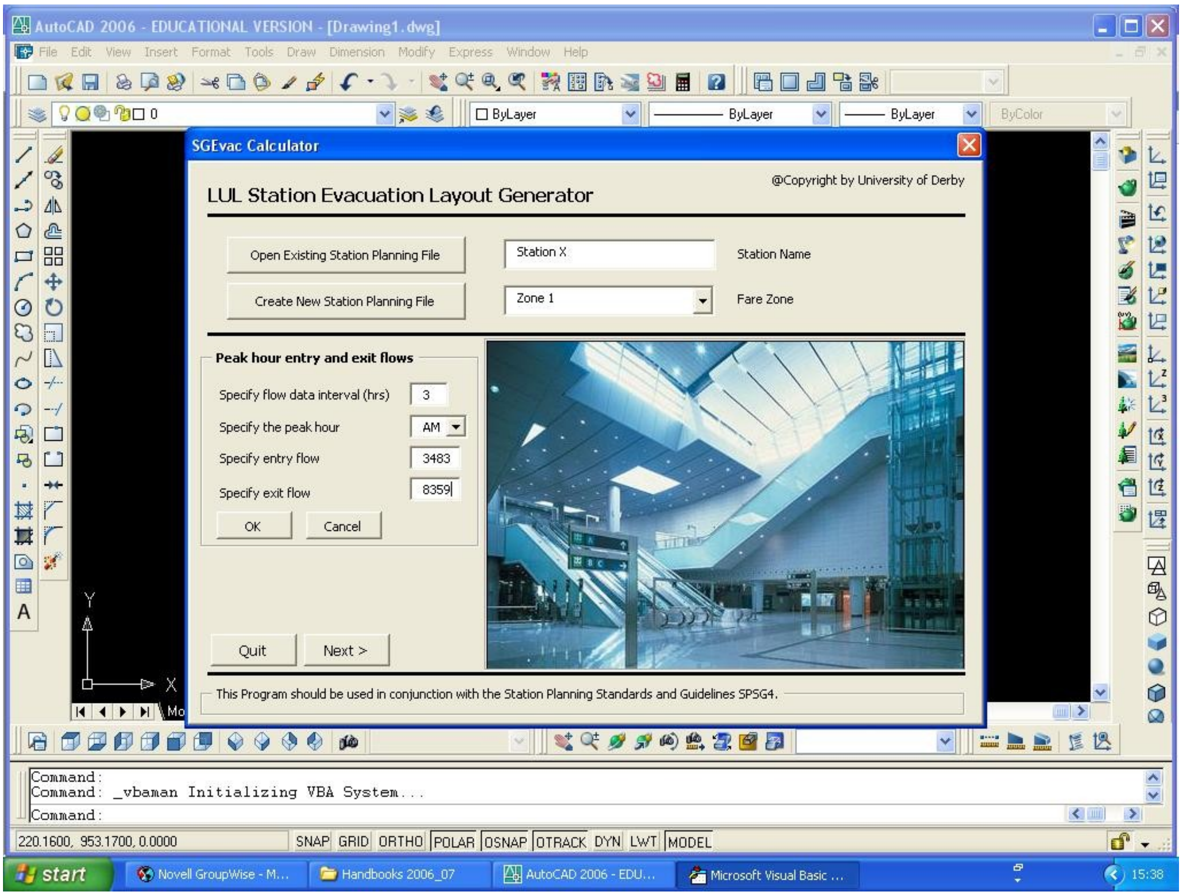


Figure 2 – SGEvac Main Screen

Figure 3 also retains the ‘open existing file’ and ‘create new file’ buttons to facilitate navigation between station designs, if, for example, a number of stations are being built or refurbished on any one railway line or similar circumstance.

The ‘*Evacuation*’ button is activated once the entire station component sizing is determined and provides for accurate sizing of exits and evacuation approach routes.

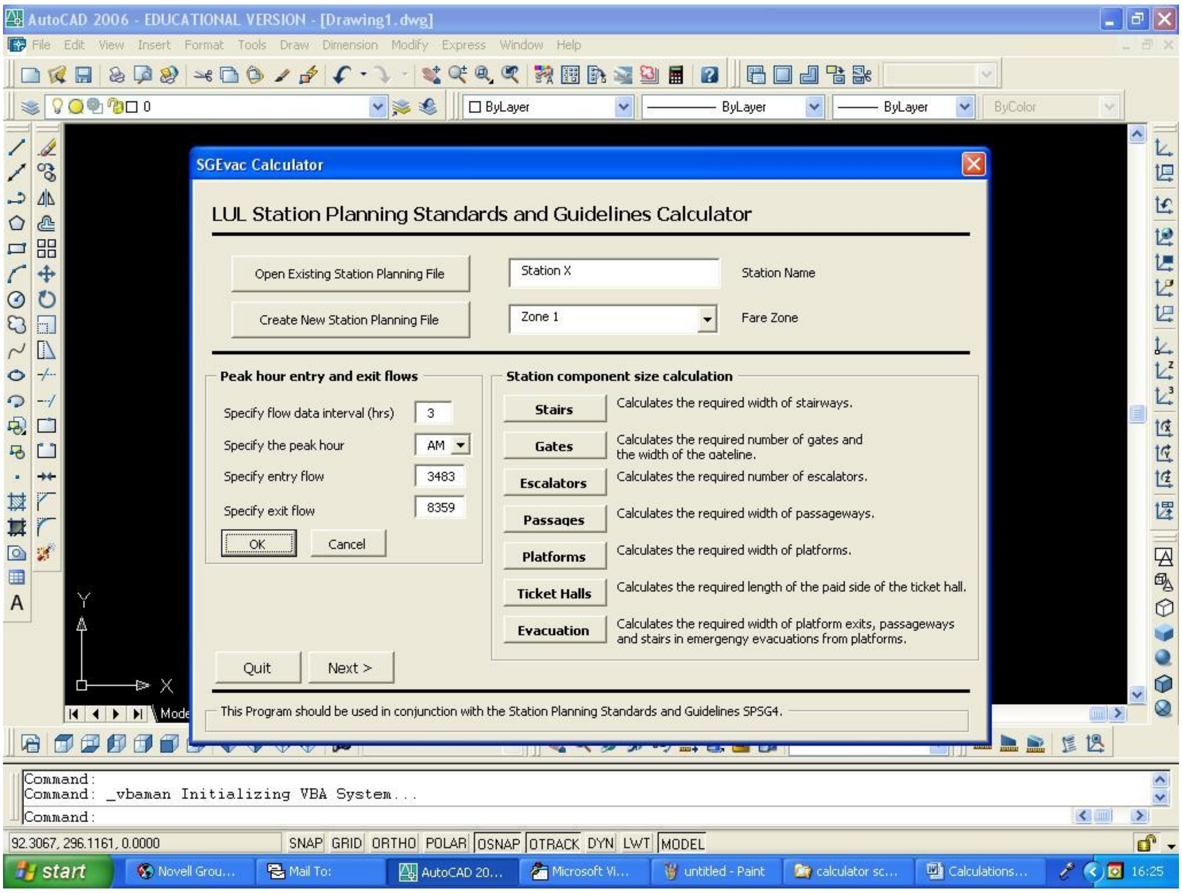
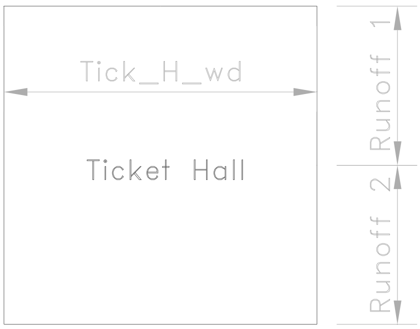


Figure 3 – SGEvac infrastructure sizing screen

SHAPE GRAMMAR ELEMENT VOCABULARY AND LAYOUT MODULE

The station shape grammar shape library / vocabulary is a fixed, finite set of station elements such as the ticket hall, platforms, passages, etc. for passenger areas; offices, mess room, toilets, etc. for non-passenger spaces; and various stores, police room, etc. for ancillary components. Consequently, whereas labelling or markers used are therefore reasonably predictable due to connection of elements governed by Standards and design guidance, the adjacency requirements for each particular situation are governed by flow rate criteria given by the designer (and so are less predictable).

A number of grammars use subdivision as the basis for the designs. This strategy is useful when designs in a language have the same, regular boundary. Other grammars use an additive process for generating designs (Knight, 1995). The grammar system used for the station layouts will use a combination of both these systems. The ticket hall composition manifested in diagrams 4-6 show how this may be achieved for a station design scenario:



The ticket hall in figure 4 highlights the two factors that determine its length and width in the SGEvac software. The Tick_H_wd (ticket hall width) is the parameter taken directly from site specific flow figures, and both run-offs are given as a set 6 metres to generate an initial shape. A 6m distance is used since the Standard for the UTS gateline (taken as the centre of the ticket hall) to street level is a 6m distance, and so is the UTS gateline to a staircase.

Figure 4 – Ticket hall initial sizing

The run-offs will change if the designer specifies a different connection (i.e. escalator instead of a stair), but these default settings allow a shape to be generated as a starting point for the initial shape and layout generation commencement.

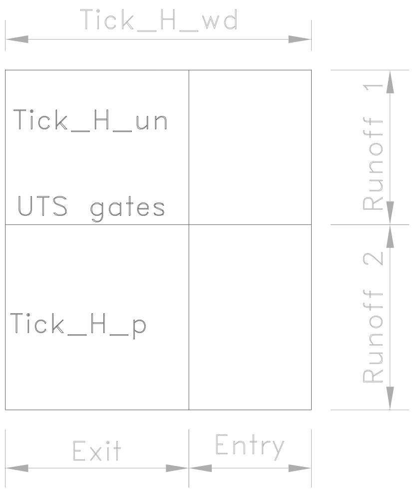


Figure 5 – Ticket hall sub-division

Figure 5 is an advancement from figure 4 where run-off No. 2 has been lengthened to accommodate an escalator run-off (say 10m in this example for a medium flow station), the UTS gateline (centre line) has been inserted and Tick_H_un (unpaid side of the hall), and Tick_H_p (paid side) have also been defined (and the ticket hall thus orientated on the site overall by the paid side of the ticket hall also being trackside to ensure LUL obtains revenue).
The number of entry and exit gates has also been specified by the designer, which in turn further partitions the ticket hall into a design space where circulation patterns can be inspected by the architect or engineer.

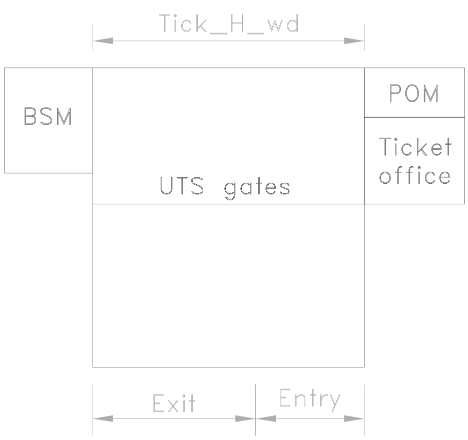


Figure 6 demonstrates addition rules. The logical position for the ticket office (sized by regulations as 11m²/per staff member) is to the unpaid side of the ticket hall, as is the POM (passenger operated machine) enclosure. The BSM (Business Station Manager) office can be located on the unpaid or paid side of the ticket hall.
The ticket office and POM are located to the entry flow side of the ticket hall to avoid unnecessary cross-over movements of people paying for a ticket and entering the paid side of the ticket hall. This can be chosen as a *policy logic statement* by the designer before the shape grammar generates any layouts.

Figure 6 – Ticket hall additions

Figures 4 – 6 begin to show a logical progression from the initial start shape (based on designer inputted passenger flow rate figures) to a ticket hall layout using a combination of shape grammar sub-division and addition rules, via application of London Underground Standards and the designer's chosen project brief *policy logic statements,* and any feasibility constraints.
In general, SGEvac utilises an additive grammar where successive parts of station elements are joined together; but elements within each station area (like gates in the gateline) will be created by division rules. Figure 7 is a flow diagram demonstrating the additive process for a staircase which is structured into a self-contained module that is linked to other station area modules in a logical sequence, where links are only made if connections are permissible in the design Standards and guidance.
The self-contained aspect of station shapes allows elements to be used individually so that the program is useful for single element refurbishments, although an inherent feature of the SGEvac system is that it benefits from multiple design steps where the markers / labels allowing connections show considerable benefit over 'traditional' designs by relatively rapid production of multiple design solutions. Sole element insertion into existing layouts reduces this benefit considerably.

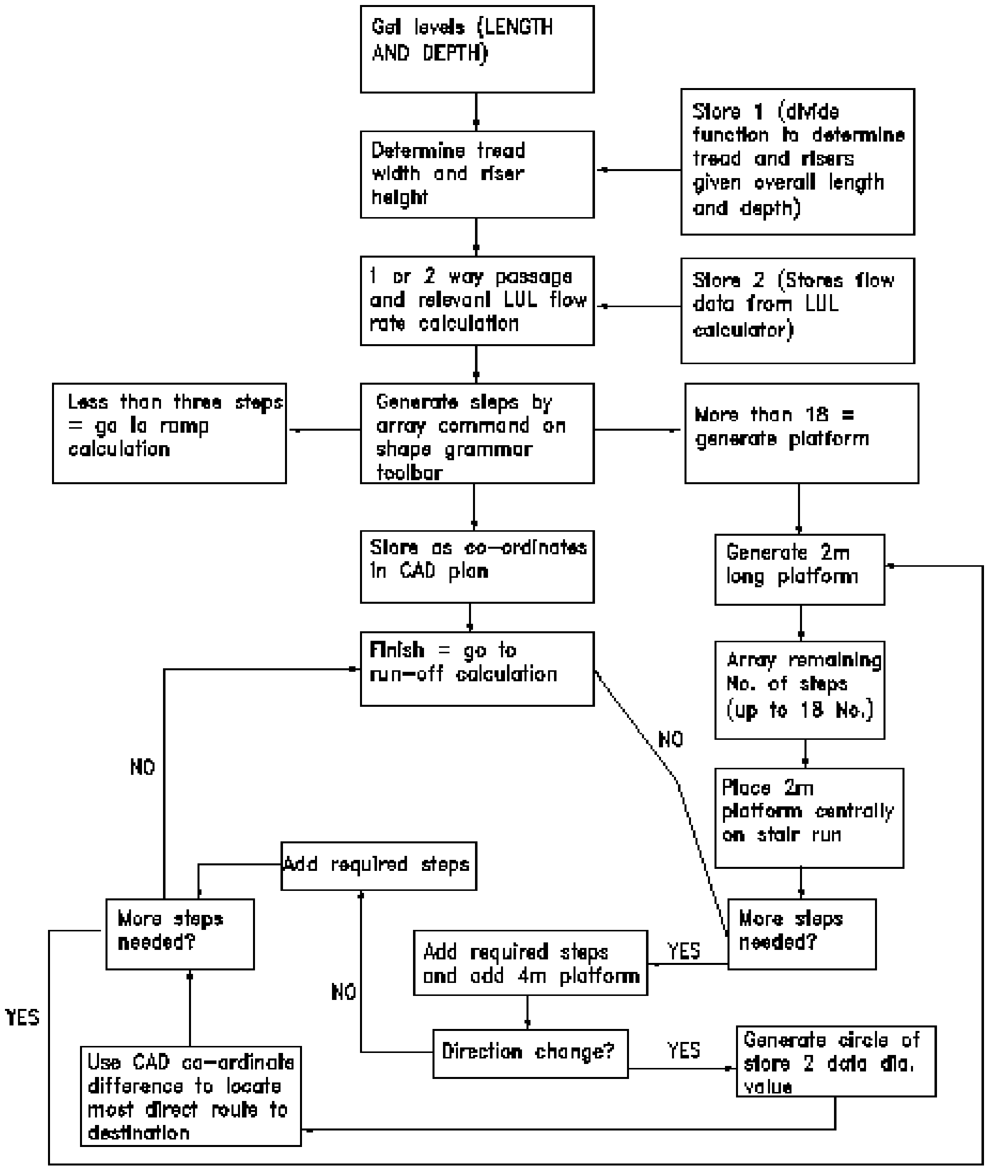


Figure 8 – Stair SGEvac generation method

Following the ‘Expert Knowledge’ Module input data, the designer is presented with the proposed ‘Layout’ Module interface as shown in Figure 9.

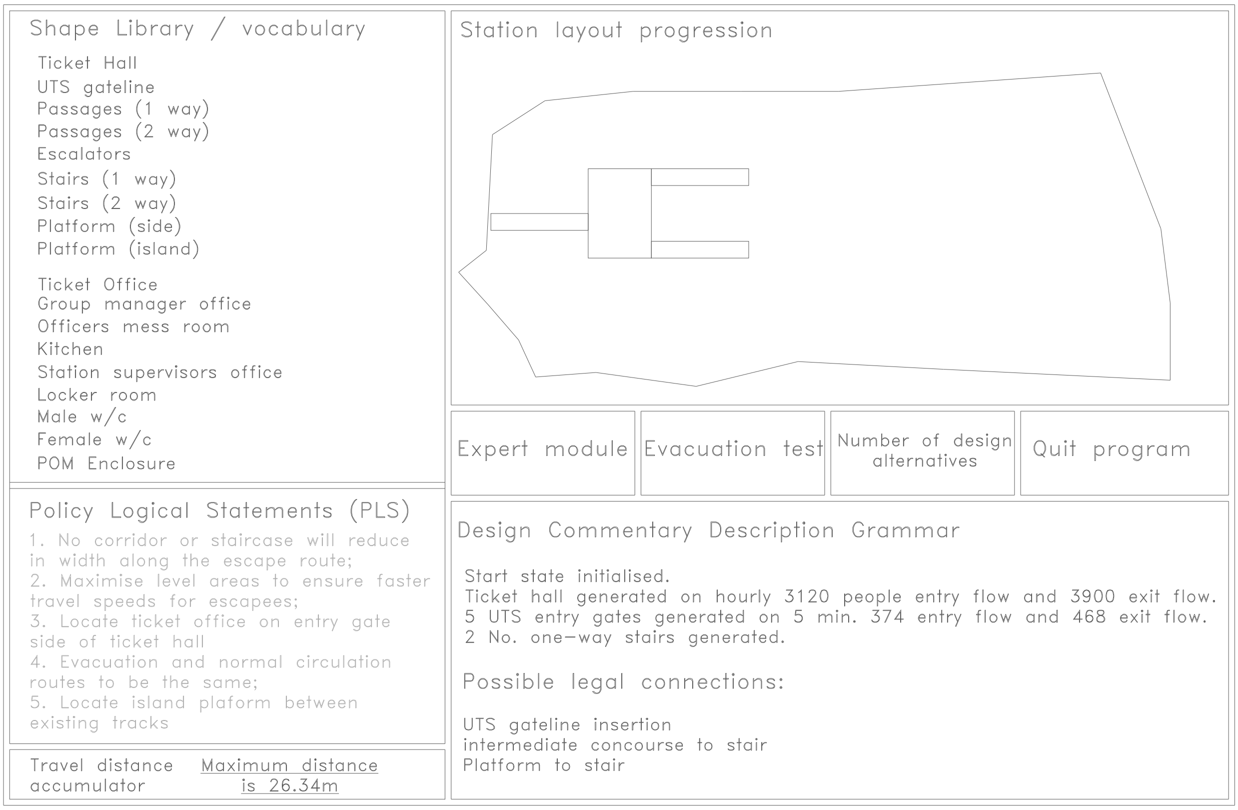


Figure 9 – SGEvac Grammar Layout Module Screen

The shape library is generated as a list from the inputted data of the ‘Expert Knowledge’ Module so that only site specific station areas are transferred into the ‘Layout’ Module. Each component has a pre-determined ‘auto number’ so that illegal connections are avoided, since each ‘auto number’ is fixed and therefore control of station area connections can be exercised inside the program structure itself. Station library components are ‘frozen’ out if the design commentary does not list them as ‘legal’ or ‘active’ connections in the next phase of the station design process.
The designer may click on an ‘active’ library component and the corresponding label or marker positions will be highlighted on the station layout progression screen where the chosen component may be located. There may only be a single label if only one connection is permissible due to site specific obstructions or Standards designating a single permutation. The designer may click on the available label(s) and the ‘active’ library component will be inserted into the design space at that position.
Clicking on another available label will show the station component in a different position, and so on. Once the desired position is obtained, the designer chooses another possible ‘legal’ connection and the previous component is listed in the ‘Design Commentary’ so that a written description of the design process is also recorded. This, to an extent, allows design knowledge to be externalised, and such discernable information allows the design process to be understood in terms of tasks and processes as opposed to merely an arrangement of shapes. All stake-holders in the project can then perceive the designer’s reasoning and decision-making.
The ‘Expert Knowledge’ Module button allows the designer to revert back to the previous module to alter any project passenger flow data or to re-define project brief requirements such as adding or removing station areas that may now or not be needed as a result of on-going design review meetings or similar event.

The ‘Evacuation Test’ button provides SGEvac’s link to the ‘Testing’ Module. This button is only used once the designer is satisfied with the design and desires to test it in the SIMULEX software. An indication of a layouts suitability for testing is the travel distance accumulator (bottom left of the screen in figure 9) which keeps a current record of the maximum travel distance as parts of the station are successively added. Its default setting is 12m - 2 sets of 6m run-offs that comprise the initial shape for the ticket hall.
The ‘number of alternative designs’ button is a combo box where between 1 and 10 design spaces may be selected. This then produces the specified number of station layout screens, layered on each other, that the designer wishes to use for layout generation purposes. Each design copies the original until the designer interacts directly with another design space, layered beneath the original screen. Other design views may be accessed by choosing an alternative number on the ‘number of alternative designs’ combo box and the station layout progression changes to the new screen so an alternative layout can be worked upon at any stage. This, for example, gives the designer an opportunity to try different options at the early stages of layout planning to take to project review meetings for discussion, and avoids lengthy option appraisals by ‘traditional’ means.

Such a method of layout generation is not automatic like other shape grammar systems, but as Grimsdale and Chang (1996) argue, the main limitation of using a grammar for spatial design is the lack of high level reasoning processes of the type seen in the rule based system.
Shape rules based on the London Underground Standards need high level reasoning, so there is inevitable trade-off between automatic generation of layouts and designer input. Due to the possibility of variation from Standards via fire engineering judgement in Designer Fire Risk Assessments it is impossible to create a set of recurrent shape rules that apply to all stations. To create such a software system would neglect the risk based approach to station design and divorce itself from credible solution states that could be used in practice by London Underground (LUL). Station shapes may be standardised, but shape grammar rules (shape arrangement) cannot model such project specific concessions, so there must be flexibility in the approach in how shape rules are applied.

Knight (1999) suggests that rule order restriction concerns when rules apply, format restriction on rules concerns component composition; so order restriction concerns connecting the various components in accordance with passenger procedures and LUL Standards and Guidelines; format restriction concerns the shape itself. An appreciation of these different categories helps to develop a suitable methodology for shape generation.

SHAPE GRAMMAR AND SITE SPECIFIC CONSTRAINTS

Figure 9 manifested a station layout progression window without any site constraints. This would seldom be the case, unless the designer has a green site at his/her disposal. London is an old city, dating from before the Roman invasion. Consequently there are not only building services, modern tower block foundations and Victorian sewer systems, but also mediaeval church vaults, archaeological sites dating back from up to two thousand years and the River Thames. Westminster station, for example, required extensive support works to prevent undermining the Houses of Parliament.

Central London is a congested city, not only above ground, but below with various mosaics of episodes layered in the ground as later developments have taken place in the area. Structural analysis, geotechnical surveys, Statutory Undertaker searches, ground contamination testing, environmental impact assessments, existing station dilapidation surveys, land take issues, etc. all need to be carried out as part of a feasibility study to determine a constraints diagram before SGEvac may be employed.

Figure 10 shows a site layout with piled building foundations to the west, electrical sub-main to the south-west, a major sewer route cutting across the site north – south-east, and the existing Permanent Way position (railway track) to the east. These elements are entered into the AutoCAD program before layout planning is commenced.

It is prudent to point out that constraints can be viewed in a positive context, in terms of services already being provided, helping to justify the business case for a new station and releasing Government money to fund investment. *Policy logic statements* may also include items such as: locate toilet areas within 10m of existing sewer route, or locate electrical plant room within 5m of existing electrical sub-main. Parameters such as these should help to direct layout production and the designer's choice of certain labels as opposed to constricting the production of many design solutions that would likely be discarded when cost engineers review proposals.

Safety aspects also form part of the feasibility study where structural engineers, in this example, have assessed the piled foundations and a 4m pressure bulb safety zone (the outer circle on each of the six piles) has been determined as an adequate exclusion zone to avoid undermining the foundation set in the over consolidated London clay.

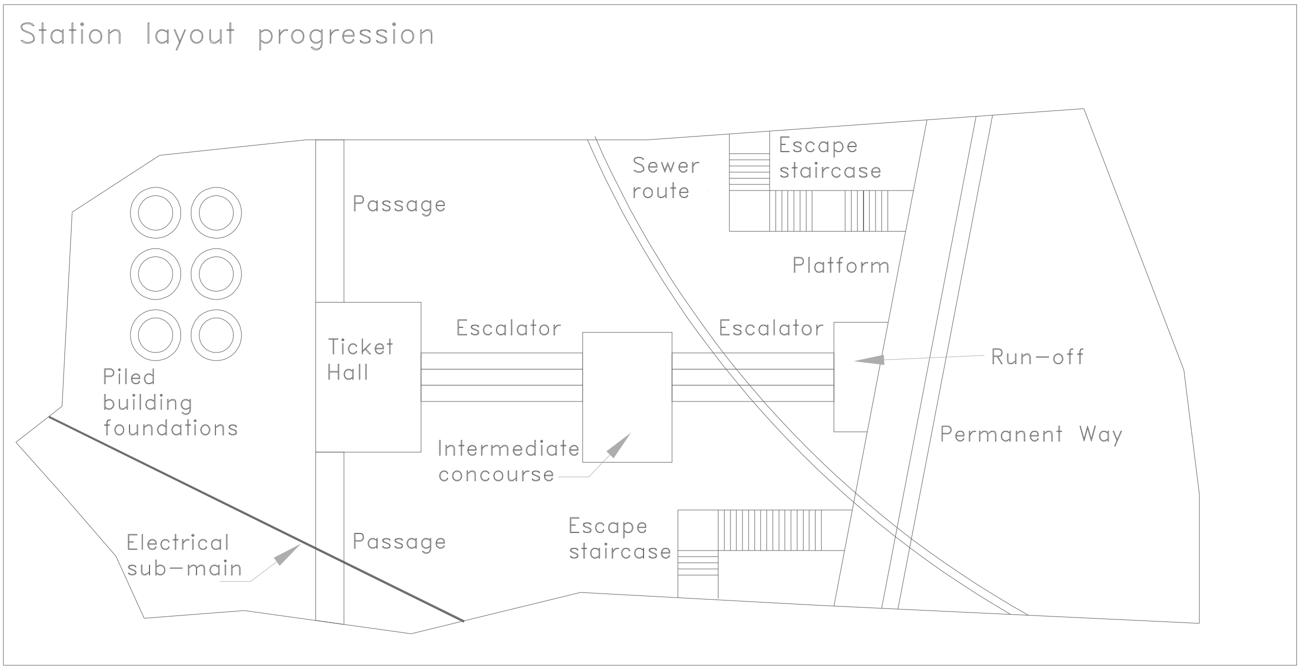


Figure 10 – SGEvac Station Layout Progression showing site constraints

Also important is the relative level of existing infrastructure to the proposed station layout. The electrical sub-main cannot conflict with the passage way itself, but can be located beneath or above the proposed passenger route to and from the ticket hall. The sewer run is fouled by the escalator and platform, but in this case it runs 1.5m below the track level and therefore does not conflict with the station layout. However, vertical distances are an important aspect in procuring credible designs and such level information must be taken into account by the designer when choosing shape grammar label options when developing layouts.

DESIGNER FIRE RISK ASSESSMENT (DFRA) INCORPORATION

Typically, the following criteria may be set as fire safety design requirements for station Reference Designs:

- Simultaneous evacuation;
- Means of escape times and travel distances compliant with E1024;
- Mobility impaired person (MIP) evacuation by evacuation lifts or ramps;
- Emergency lighting and signage to comply with E4451 and E4201 respectively;
- Fire detection and alarm installations to comply with E1405, with warning provided by combined public address and voice alarm systems;
- Natural smoke clearance from lower concourses, non-public areas and retail units;
- Materials and finishes to comply with E1043;
- Compartmentation to meet E1407;
- Fire suppression to sub-surface stations by means of sprinkler and water-fog systems to meet E1406;
- Fire-fighting access to surface stations via escape stairs and sub-surface stations via one pressurised fire-fighting shaft per platform to comply with E1419; and
- Fire-fighting equipment to comprise dry fire mains to platforms, hose reels to ticket halls and portable extinguishers throughout to comply with E1404.

Modelling such a varied list of requirements is outside the scope of SGEvac, but the list serves to illustrate the complex nature of fire safety design requirements that construction industry professionals must deal with to procure stations, and their interaction into one spatial layout design will inevitably lead to 'trade-off' between parameters so that application of Standards and guidance documents suit the particulars of each site. The trend away from prescription to risk based judgement moves spatial layout planning tools such as shape grammar to a position of inter-dependency with other design criteria: neither can be formulated in isolation from the other. This reinforces the view of Chang and Grimsdale, since station design cannot be viewed as a straightforward arrangement of generic shapes in set rule permutations if SGEvac is to become a useful design tool in practice.

SYSTEM DEVELOPMENTS AND FUTURE DIRECTION

The DFRA incorporation is an important aspect to the 'Layout' Module interface and requires further liaison with Underground fire safety engineers and practising architects designing stations in how such varied criteria is allied with layout planning. This is particularly important where deviation from Standards occur.

Vertical constraint issues such as those presented in diagram 10 require review and possible incorporation in the SGEvac software. An isometric or section view of the proposed layout, with pre-determined parameters also in place, may aid with this aspect of layout planning problem solving.

The 'Layout' Module interface itself would benefit from liaison with designers of Underground stations and their trial of its use so that feedback can be reviewed and the interface possibly improved.

FIRE EVACUATION SIMULATION RESULTS USING SGEvac LAYOUTS

The ‘Testing’ Module, comprised of AutoCAD drawing exchange into SIMULEX software, has not been used to date since the ‘Layout’ Module is still under construction. However, diagram 11 shows a station layout transferred into SIMULEX, with an evacuation scenario in progress. This type of ‘traditional’ design shows crowding build-ups at the base of escalators and the escape stairs.
It is not the intention of the SGEvac approach to review designs and alter localised problem areas of congestion, but to provide whole station solutions where passenger flow is maintained as constant to facilitate overall faster egress times. London Underground stipulates that passengers should be able to clear the immediate vicinity of a fire within four minutes, and reach a place of safety from smoke or toxic fumes within six minutes.
The layout below meets these criteria, but regulatory compliance is a minimum of what must be met, whereas SGEvac seeks to drive evacuation times down as far as possible (within reason, and with respect to the requirements of the project brief).

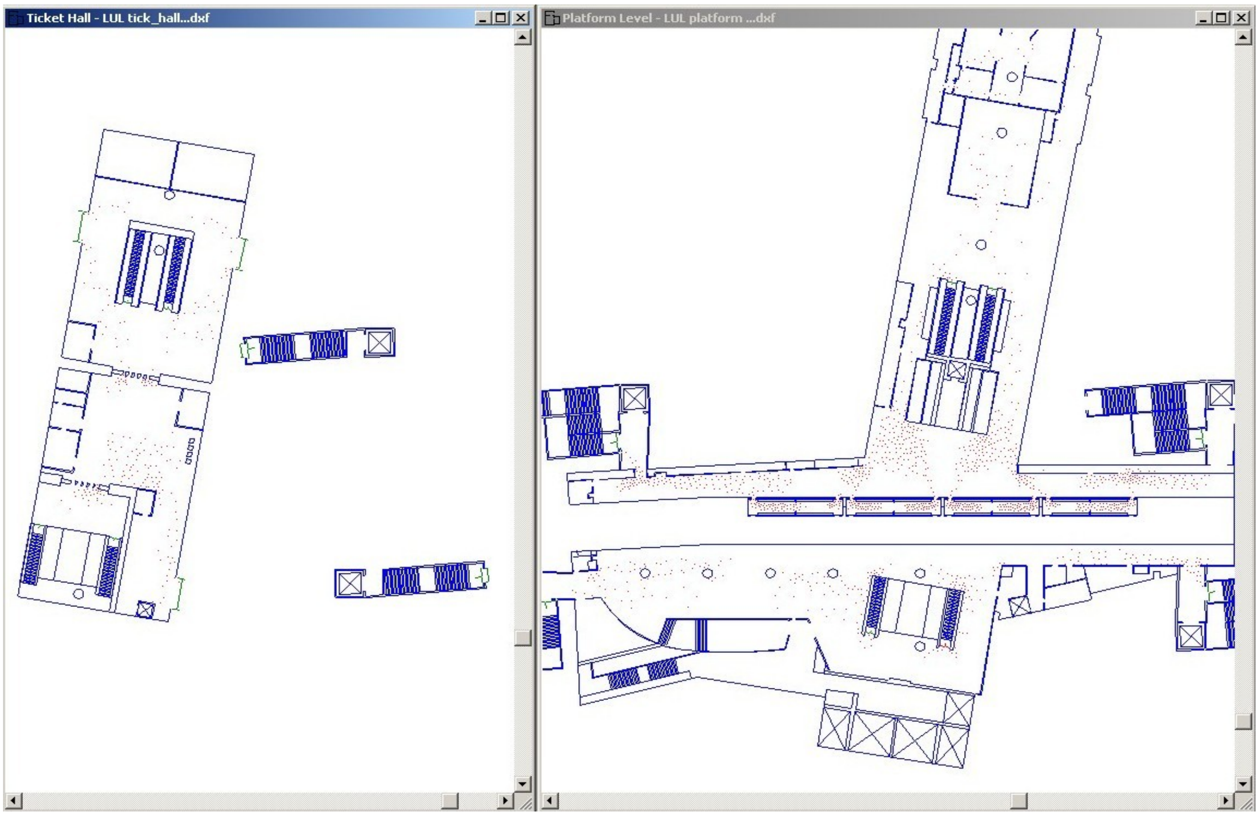


Figure 11 - Station Evacuation after 25 seconds in SIMULEX software

CONCLUSIONS

London is only one of four ‘Alpha’ world cities and has one the largest, oldest and most complex underground railway systems in the world. The system has an excellent passenger safety record since opening in 1863, its two most notable tragic events taking place at King’s Cross in 1987 and the terrorist attacks of 7th July 2005.

The proposed, novel shape grammar approach is unlikely to have a major impact on Central London stations due to many site specific constraints and interchanges between stations creating an array of pre-determined parameters. However, site

constraints can be viewed positively inasmuch as determining layout as opposed to constricting it.
Passenger accessed areas are generally sized by demand, whereas non-passenger spaces and ancillary station units are sized by regulations, and are only included in designs via project brief requirements. Project specific station components are transferred from the 'Expert Knowlegde' Module to the 'Layout' Module where *policy logic statements* can also help the designer to direct design to facilitate faster emergency egress times.
The description grammar in this module, to an extent, allows the externalisation of design knowledge, allowing the design process to be understood in terms of tasks. All stake-holders in the project can then perceive the designer's reasoning and decision-making. Logic is fundamental to the design process for this building type and a clear understanding of the key constraints and parameters is central to establishing a base diagram.
Addition and division rules are employed to generate layouts and labels / markers provide the mechanism to manifest permissible connections and the number of alternatives to the designer where such 'legal' connections may apply. Multiple design solutions can also be created relatively quickly when compared against 'traditional' means.
Future research includes incorporating the complex and varied requirements of fire engineering risk assessment criteria and liaison with Underground station designers in order to test the 'Layout' Module interface. Vertical constraint issues also require further consideration and possible incorporation into SGEvac.

ACKNOWLEDGEMENTS

Jacobs (UK) Ltd. (c/o Mr. Mike Grimsey);
London Underground Ltd. (LUL);
Strategic Rail Authority (SRA).

LUL and SRA have not reviewed this paper and the content is solely the work of the authors. London Underground Ltd. is acknowledged for providing the design guidance that is reproduced in this paper. The Strategic Rail Authority is acknowledged for authorising use of station layout plans. Both their help is deeply appreciated.

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