

Application of Shape Grammar Theory

to underground rail station design and passenger evacuation

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Abstract This paper outlines the development of a computer design environment that generates station ‘reference’ plans for analysis by designers at the project feasibility stage. The developed program uses the theoretical concept of shape grammar, based upon principles of recognition and replacement of a particular shape to enable the generation of station layouts. The developed novel shape grammar rules produce multiple plans of accurately sized infrastructure faster than by traditional means.

A finite set of station infrastructure elements and a finite set of connection possibilities for them, directed by regulations and the logical processes of station usage, allows for increasingly complex composite shapes to be automatically produced, some of which are credible station layouts at ‘reference’ block plan level.

The proposed method of generating shape grammar plans is aligned to London Underground standards, in particular to the Station Planning Standards and Guidelines 5th edition (SPSG5 2007) and the BS-7974 fire safety engineering process. Quantitative testing is via existing evacuation modelling software.

The prototype system, named SGEvac, has both the scope and potential for redevelopment to any other country’s design legislation.

Keywords: *layout improvement; station design; fire evacuation; shape grammar*

I. INTRODUCTION

Underground railway stations are designed manually for a particular site and brief, with production of alternative options being a relatively lengthy process. Yet with rapid egress from stations so critical, it is preferential for accurately sized multiple layout design solutions to be produced at an early stage for scrutiny.

Mass transit rail systems must also be planned to avoid congestion in normal operating conditions. Hence there is also a need for improved layouts in this more frequent scenario.

Station buildings may be considered in terms of functional spatial layout planning, task sequence and deductive reasoning, since it is the passenger capacity calculations that are used to size infrastructure. Area and adjacency requirements are deduced through understanding logical passenger processes, with non-passenger spaces linked by station operation functionality. It is use of this prescriptive approach that allows for a transition from ‘traditional’ layout planning to a proposed shape grammar layout generation method. Stations have a principal aim to transport and receive the system’s users to/from their destination as quickly and efficiently as possible. However, achieving this aim must not be detrimental to passenger safety, which is paramount in station design.

However, there is a global move away from prescription to a performance based approach in fire safety, and shape grammar rules cannot model project specific concessions made by such performance based high level reasoning (engineering judgment). Consequently, there must be a trade-off between automatic generation of layouts and designer input within the program constructs. In this context the SGEvac programme is intended to be a design aid tool, not a substitute for designers.

II. SHAPE GRAMMAR & THE SGEVAC SYSTEM

A. *Shape Grammar*

Shape grammar is a general computational formalism that manipulates shapes to generate designs [1]. The concept of shape grammar is conceived as a way of describing and creating languages of designs where shapes are devices for visual expression – as symbols are used for verbal meaning. The concept is mainly attributed to Stiny and Gips in [2], with major contributions made by Stiny [3], [4], Fleming [5], Knight [6], [7] Chase [8], Tapia [9], Liew [1] and Li [10].

Shape grammar development begins with a vocabulary of shapes and the definition of spatial relations between these shapes. Spatial relations constrain the ways that vocabulary elements may be combined with one another. They are simple compositional ideas and are the key to shape grammars [7].

Application of grammars range from simple rectangular blocks as shown in Figure 1, to Chinese lattice windows [3], to African homesteads [11], to Roman cities [12].

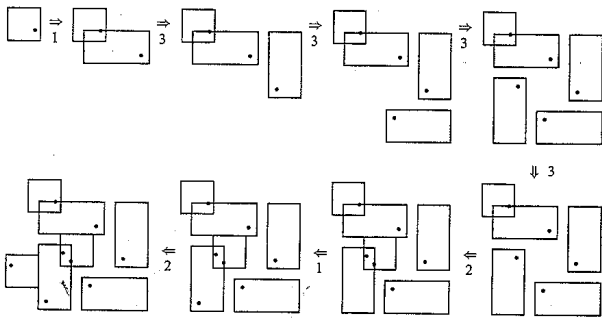


Figure 1 – A shape grammar rule and its recursive applications [7]

Practical examples of architectural shape grammars have largely reviewed classical building styles such the houses of the Queen Anne period [5] or Palladian villas [13].

Figure 1 shows how shape grammar functions to create designs. The black dot on the initial shape is a label that only allows certain rules within a shape grammar language. These labels are devised so that suitable descriptive functions can be procured within set parameters. The descriptive functions are the shape rules, where a rule may be understood as having a meaning in a design, such as a corridor connecting to a kitchen. The labels shown in Figure 1 show the systematic composition of an additive shape grammar, applying a shape rule sequence where the position of the next artefact is dictated by the labels.

Figure 2 shows previous examples of grammars spread across various categories, underpinned by process or pattern.

Based on the shape grammar research undertaken, the methodology for SGEvac follows a six-stage generic logic model approach, as described in [14].

1. **Identification** (from experts' opinion, regulations, etc);
2. **Conceptualisation** (interrogating information and choosing the shape grammar type and theorising rule development to provide layout diagrams);

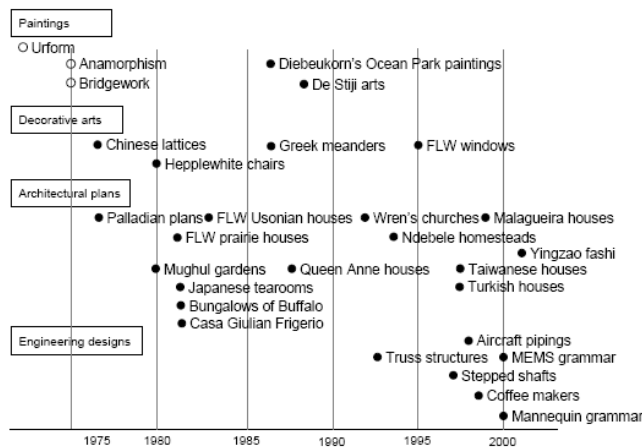


Figure 2 – Example of Shape Grammar Applications between 1975 and 2003 [15]

3. **Formalisation** (designing / specifying the shape grammar system with respect to underground station components);
4. **Implementation** (developing and implementing the mathematical rules for computerised shape grammar rules and labels);
5. **Testing** (for the computerised system and fault finding);
6. **Experimentation** (as emergent features come to light in the shape grammar generated layouts).

III. SGEVAC IDENTIFICATION AND CONCEPT STAGE

A. Identification Stage

Shape grammar rules lend themselves to prescription, bound by the prescriptive nature of the English & Welsh Building Regulations and London Underground design guidance SP5G5 (2007). These were the primary documents used to create the rules for SGEvac.

B. Conceptualisation Stage

The Conceptualisation of SGEvac took into account two main phases:

- The work of Fruin [16] with respect to passenger processes and layout planning using an additive grammar [7].
- Specifying the interconnection of station areas to permit formal translation into shape rules.

C. Fruin data, passenger processes and shape grammar type

Underpinning the SP5G5 is the detailed pedestrian flow analysis of Fruin, categorized into Levels of Service (LoS).

Level of Service A in Figure 3 represents free circulation. Levels become more restrictive in terms of people movement from B to E, with level F representing a situation with numerous stoppages.

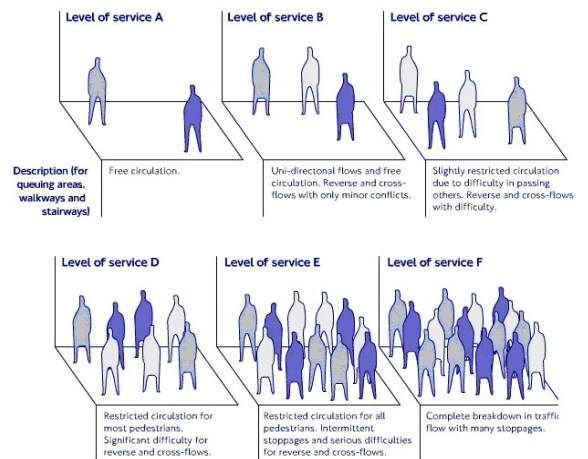


Figure 3 – London Underground Levels of Service [17]

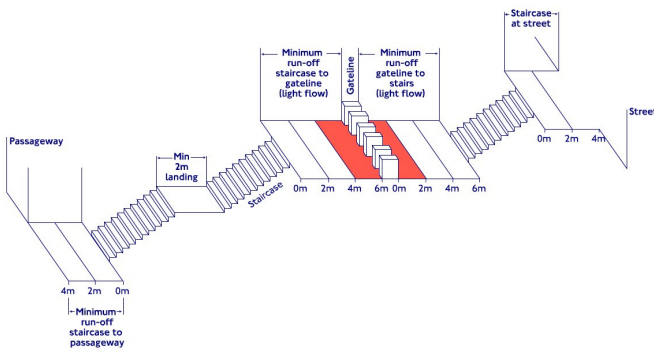


Figure 4 – Selective Run-off Distances for Station Areas [17]

An explanation of passenger processes may be précised as entering the complex from the street, usually via a stair. A one- or two-way passage then provides access to the unpaid side of the ticket hall where passengers buy a ticket before passing through the UTS gate line to the paid side of the concourse.

Passengers then descend stairs/escalators/lifts to platform level, and 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 (see Figure 4), as specified in SPSSG5 (2007) depends on the passenger flow capacity of the vertical interchange element and its connecting station area [17]. This route is reversed when people wish to leave the system.

These processes demonstrate that simple, underlying rules provide the framework for seemingly complex metro station designs. Much of the complexity in underground station layouts is due to the existing site constraints that are discussed in section V of this paper.

Non-passenger areas are also incorporated in the SGEvac shape grammar developed in this research. These spaces are connected to the main station plan via any stipulations that exist in design standards and guidance documents, or in the absence of prescription, by logical reasoning.

SGEvac uses an additive process for generating designs [7]. This method is particularly suitable when designs in a language have irregular boundaries or when different designs have different boundaries like a one-off station site.

Furthermore, restricted types of grammars with a minimum of parameters and labels may best be suited for the early conceptual design stages [6]. Rules are straightforward to design and understand, but they are still capable of generating innovative design possibilities.

Generated designs can be elaborated either by further specifying the grammar or by traditional means. Stiny [4] supports that rules open up new avenues or directions for design within a given vocabulary, increasing the designer's power of observation.

To be used in practice, SGEvac must not only align to fire safety engineering methodologies, but also allow a transfer of skills from a traditional approach by maintaining a good correspondence between the proposed rule based system and logical, deductive design strategies for rail station design.

D. SGEvac Algorithm

The prototype algorithm has been developed as three bespoke modules – *Expert Knowledge*, *Layout and Testing*, to deconstruct qualitative, quantitative and validation processes. Figure 5 summarises this process.

The 'Expert Knowledge' module principally incorporates the SGEvac Identification Phase design documents. These standards are then assessed against the project brief and site constraints that have been deduced from a feasibility study before layout planning would begin. Predicted peak passenger flow rates define the size of infrastructure at this stage, and, once specified, the infrastructure can be sized and subsequently stored in the 'vocabulary library' in SGEvac's layout generator.

The shape grammar generations commence once all pre-determined data are stored in the program. The designer is able to choose the number of alternatives that are to be generated.

Engineering judgment is used to evaluate the generated designs, with a decision taken on suitable layouts to export to the 'Testing' module. Selected spatial layouts will be used to evaluate the designer's intuitively preferred layout(s) by running it / them through an evacuation software package.

If they provide satisfactory results, the preliminary designs are sent to the client for approval, whereas if results are unsatisfactory the design team re-evaluates the station plan and has the facility within SGEvac to make alterations based on expert judgment.

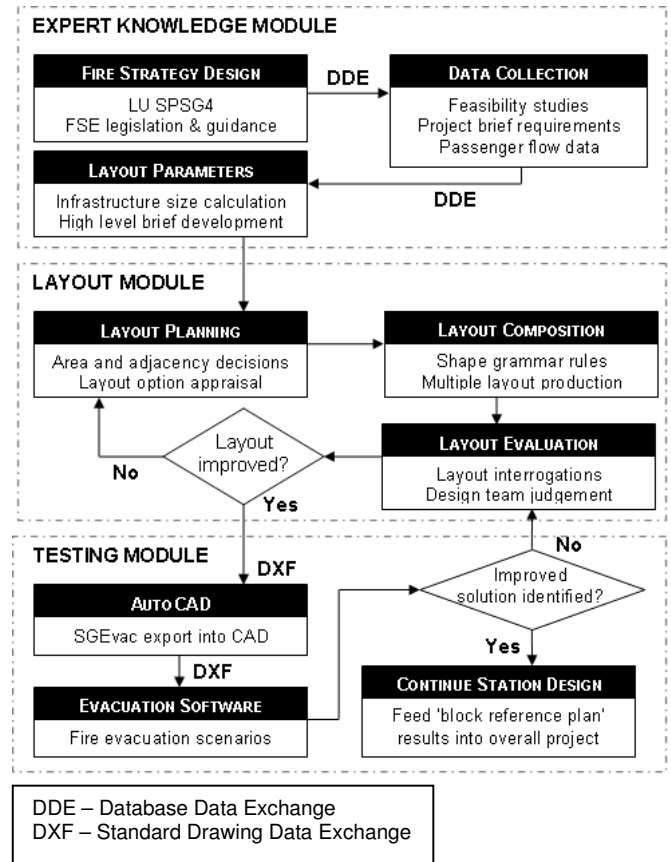


Figure 5 – Proposed SGEvac algorithm

There is also an option to take a further step back to the layout planning stage if this is considered beneficial for the project.

IV. FORMALISATION STAGE

The Formalisation stage includes:

- The scheduling of rule connections to align with standards;
- Rule manipulation techniques within the program architecture to enable its use by the design team;
- The specification of the SGEvac algorithm that will enable designs to be generated.

Table 1 shows an example of a schedule of the ‘primary’ and ‘secondary’ connectable elements permitted in the SGEvac system. The run-off rule has seven different connection possibilities, with the selection of the rule driven by the vertical height they need to bridge and the peak passenger flow capacity they need to accommodate.

For example, an escalator to run-off connection is selected for use in the design by SGEvac rules if the designer specifies a vertical distance in excess of three metres and the maximum passenger flow is 3,000 people or above, counted over a three hour time interval. These boundary limits are aligned to LU standards, as specified in SPSG5 (2007).

The scheduling is also partitioned into groups to support a modularised approach to programming and to mirror design practice methodology.

Groups are arranged into passenger, non-passenger and ancillary sections. The non-passenger elements are further divided into suites, being allocated as Group Station Manager, Ticket Office, Mess Room and Safety Representative suites to suit the connection patterns. Ancillary and passenger areas are sub-categorised into two suites, also based on logical connectivity.

	SGEvac Area Connection Schedule		
	Shape Rule Name	Primary connect	Secondary connect
	SR_STREET_01	Street level	Run-off
	SR_STREET_02	Street level	Lift lobby
	SR_R-OFF_01	Run-off	Escalator
	SR_R-OFF_02	Run-off	Stairs
	SR_R-OFF_03	Run-off	Travelator
	SR_R-OFF_04	Run-off	Platform
	SR_R-OFF_05	Run-off	Intermediate concourse
	SR_R-OFF_06	Run-off	Lift lobby
	SR_R-OFF_07	Run-off	Ticket hall

TABLE 1. FORMALISATION OF SHAPE RULE CONNECTIONS

Station Area	Ticket Office Group Connection Schedule		
	Shape Rule Name	Connected component	Group allocation
Ticket office	SR_TO_01	Ticket hall	TO
	SR_TO_02	POM enclosure	TO
	SR_TO_03	Ticket sellers’ room	TO
	SR_TO_04	GSM office	TO
	SR_TO_05	Police room	TO
	SR_TO_06	Ticket office toilets	TO
POM enclosure	SR_POM_10	Ticket hall	TO
	SR_POM_11	Ticket office	TO
	SR_POM_12	Paper store	TO
Paper store	SR_Pap_st_01	Ticket office	TO
	SR_Pap_st_02	POM enclosure	TO
TSR	SR_TSR_01	Ticket office	TO
	SR_TSR_02	Ticket sellers mess area	TO

TABLE 2. TICKET OFFICE SUITE SHAPE RULE CONNECTIONS

Table 2 shows part of the Ticket Office component schedule.

Rule Manipulation Techniques

SGEvac operates in two-dimensions, since this is how most shape grammars and all underground stations are designed. Station layouts are often uni-directional to aid with managing large flows of people; therefore the major passenger area components of the station should not overlap when changes in level occur. These are the important station areas as far as evacuation is concerned.

The information that drives much of the SGEvac process is the site boundaries, peak passenger flow numbers and the relative depth of the platform, ticket hall and street level. The site boundaries dictate the extent of where the automatically generated station plans can be located, and the peak passenger numbers are interrogated over certain time intervals to size infrastructure.

For example, a two-way staircase is assigned a Fruin level of service C, allowing 38 people / minute / metre width to use this piece of infrastructure. The site specific size of the two-way stair is sized by a peak one minute passenger flow, which has various correction factors (margins of safety) assigned to it as passenger numbers are rounded down from one hour, to fifteen minutes, to five minutes. Various infrastructures are sized using these intervals, and SGEvac uses the various formulae accordingly, also taking account of the LU fare zones since inner City stations have greater passenger demand, and hence greater safety margins.

The shape grammar system assumes all final exits are at ground level, with the ticket hall and platform(s) being the other two ‘landmark’ elements that require the user to determine their depth relative to the final exits.

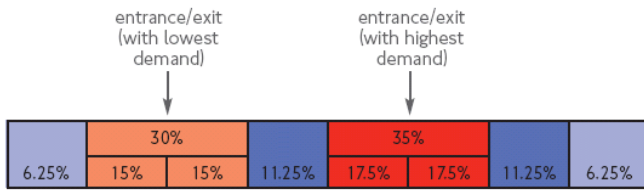


Figure 6 – Variable Passenger Distributions on Platforms [17]

In so doing, SGEvac selects the correct interchange components by an event driven mechanism that evaluates the height change and passenger volume demand between these three principal areas.

Escape distances from platforms (the worst case travelling distance scenario) 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. The shape grammar labelling is controlled via the connections made available in the rule specification schedules.

Platforms vary in length, depending on the rolling stock that is used on each line. The maximum platform length is 140m, so SGEvac uses this value as a base although it can be corrected by the designer if it should be shorter. LU studies have concluded that many people congregate in the central areas of the platform, as shown in Figure 6.

In addition, SGEvac passenger area layout production may also be user controlled, since a completely automatic system cannot cater for all possible site constraints.

In terms of vector magnitude, interchange infrastructure must connect to the adjoining station area by at least two co-ordinate corner points. Therefore the restrictive labels will prevent a passage, for example, only aligning a proportion of its width with the ticket hall. This would unduly constrict passenger flow at the head of the passage.

Non-passenger and ancillary areas that are sized by regulation use isometric transformations of translation and scaling to generate the suite layouts. For example, the mess room is 11.5m² in area for 4-10 staff, 21.5m² for 11-25 staff, 32.7m² for more than 26 staff. This results in a minimum size as a starting point, but should the user specify a number of staff that would exceed the thresholds noted above, SGEvac automatically re-sizes the station area to suit.

V. SGEVAC PRACTICAL APPLICATION TRADE-OFF

This section reviews the Identification to Formalisation phases from a fire safety perspective in order for the reader to appreciate the integration of SGEvac spatial layout planning into performance based fire safety engineering (FSE) objectives.

Before FSE, the traditional Building Regulations approach was to identify certain components and incrementally prescribe standards to them, achieving compliant designs by providing a large number of exits at relatively short intervals. By contrast, a fire safety engineered approach estimates the required time to leave the building as opposed to relying on prescribed

assumptions. Consequently a risk based approach for FSE has become predominant in the rail industry. It reintroduces design flexibility and potential cost savings without detriment to life safety. SGEvac responds to this global trend by allowing flexibility at the graphical user interface (GUI) so that dispensations agreed between designers and approving authorities can be modelled.

For example, heavily constrained sites that need to contend with piled building foundations, sewer runs and connection to existing underground infrastructure need a degree of human intervention to formulate credible solution states.

Due to the nature of London Underground stations' long travelling distances created by the nature of the facility to accommodate trains at platforms, BS 7974 is used to justify acceptable levels of safety in new designs and major renovation projects.

A qualitative design review is undertaken to scope the parameters of an FSE project to define acceptance criteria such as trade-offs in travelling distances, or refinement of the building structure to resist higher temperatures, or planning the layout to manage the fire and smoke spread, etc. These goals can then be proven by calculation or computer modelling until a satisfactory result is obtained that meets the acceptance criteria of the authorities.

Table 3 shows the comparable stages of development between SGEvac and BS 7974 so that the design team understand where shape grammar fits into the project framework.

For example, the barriers could be positioned to segregate crowd flows to more manageable levels, although if used inappropriately, they could form a trap where movement of the crowd is undesirably restricted. Fruin [19] substantiates that code compliance alone does not guarantee that a building will function well during normal use or emergency egress, which justifies the role of SGEvac as a design aid that complements engineering judgment.

	Methodology Alignments		
	BS-7974 Process	Logic Model Process	SGEvac Process
1	Assess benefits/start	Identification	Project brief; identify need for SGEvac
2	Qualitative Design Review	Conceptualisation	Station system component identification and interactions
3	Quantitative analysis	Formalisation	Legislative compliance/ area assignments/ passenger flow figures
4	Satisfactory/ Unsatisfactory	Implementation	Station layout generations
5	Report and Review	Testing	Testing and validation of layout generations
6	End	Experimentation	Experimentation with validated layouts/ Iterations/ improvements

TABLE 3. METHODOLOGICAL ALIGNMENTS

Designing for crowd management requires projected maximum occupancy levels of a space to be correlated with the movement capabilities, for all corridors, stairs, ramps, escalators and other facilities. The SGEvac model is an extension of this, whereby such schematic diagrams are replaced with layouts that are sized accurately and with respect to LU passenger flow figures and design standards. Fire evacuation modelling is then used to validate produced reference plans and layouts.

VI. IMPLEMENTATION STAGE

The SGEvac design environment uses object-oriented programming, which is suitable for shape grammar, and it is modular – thus lending itself to partitioning ‘connectable’ shape rules per station element.

Figure 7 shows the SGEvac main user graphic interface. The station name, description and fare zone are entered by the user along with the ticket hall, platform depths and the overall site boundaries. The ticket hall may be at street level, and if this option is chosen the interface locks the ticket hall depth field to avoid producing an invalid solution. Peak passenger flow figures, over a time interval of 3 hours are also specified, as stipulated in SPSG5 (2007).

The relative depths of the two ‘landmark’ station areas of ticket hall and platform allow the program to select the correct interchange component in conjunction with the peak passenger flow figures.

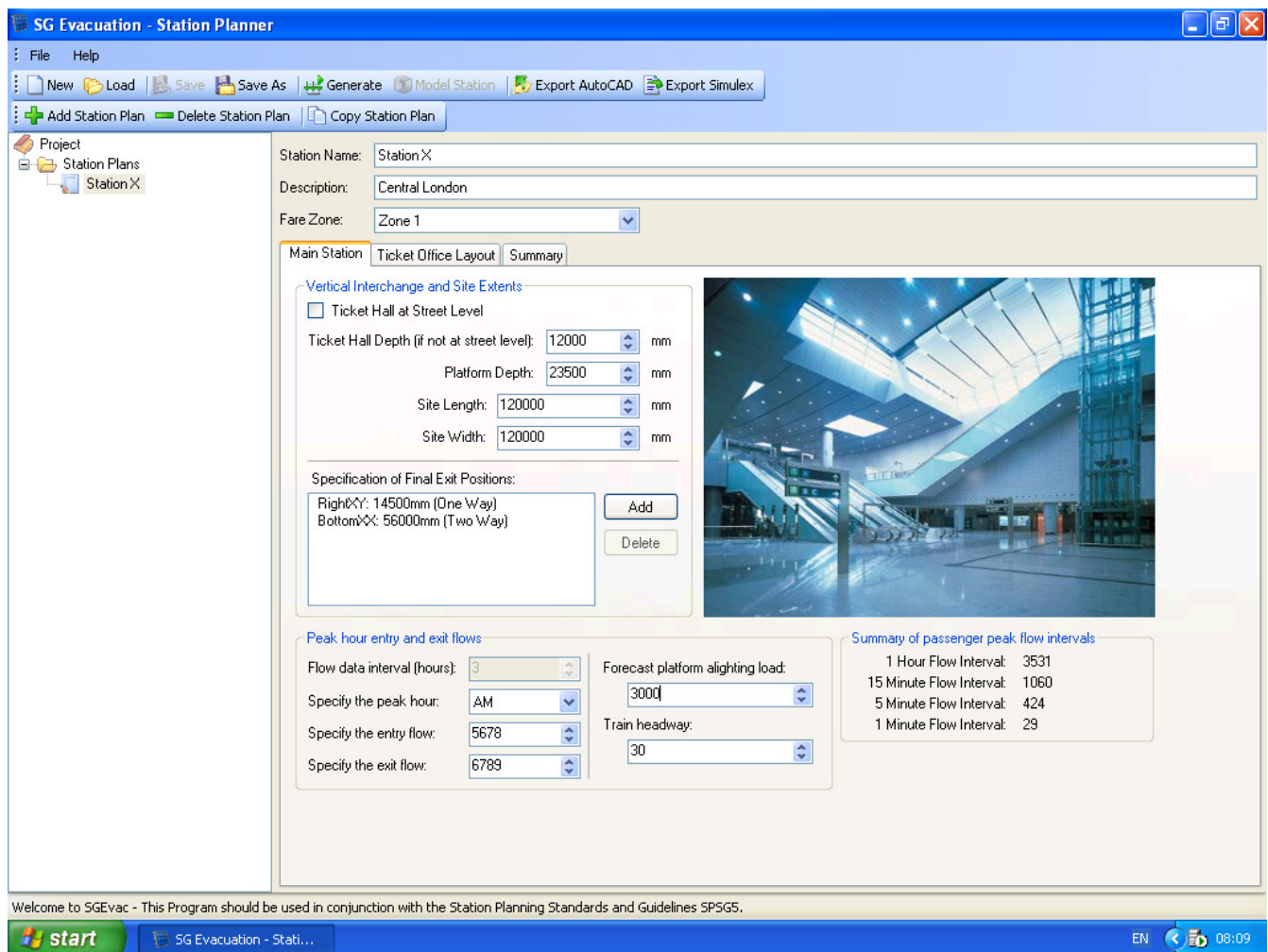


Figure 7 – SGEvac Expert Knowledge Module Screen

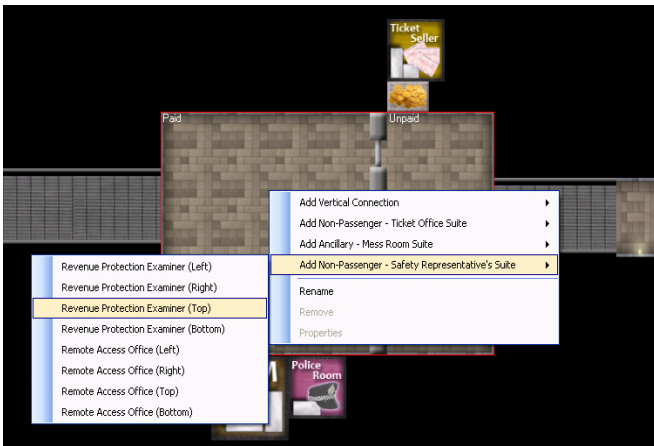


Figure 8 – SGEvac Properties Window

If escalators are chosen the program has a safety aspect where no escalator can exceed allowable height to minimise the risk of a passenger cascade. Stair landings are also included in the SGEvac formalism (a 2 metre landing after 12 steps, and a 4 metre landing after two flights of steps and changing direction) to comply with standards.

Several versions of passenger area auto-generated layouts are accessible from the 'Expert Knowledge' screen, allowing various permutations, and incremental improvements to be analysed by the design team.

Grammar labelling in the 'Layout' module is multi-faceted due to the various possible connections within SGEvac. The component suites are accessed from menu-bars to allow shape union of legislative compliant areas as shown in Figure 8. This diagram shows four connection possibilities, one to each wall of the ticket hall for the revenue protection examiner room.

Non-passenger and ancillary properties are available via a property window for each station element, with the ticket clerk's office properties window shown in Figure 9. Access to these screens makes possible the re-sizing of staff areas based on the number of people who use it.

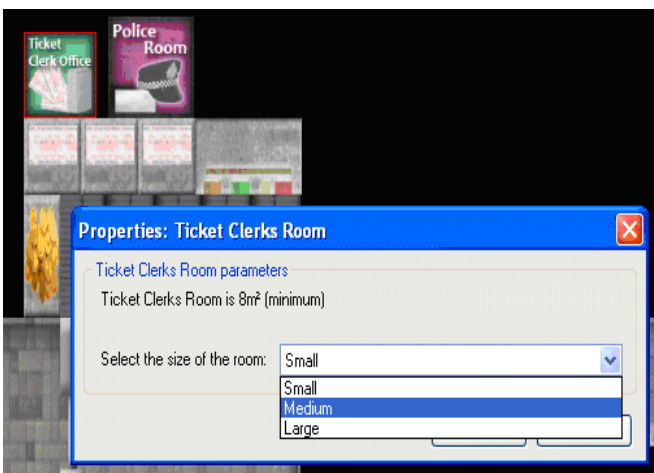


Figure 9 – SGEvac Ticket Clerk's Room Properties Window

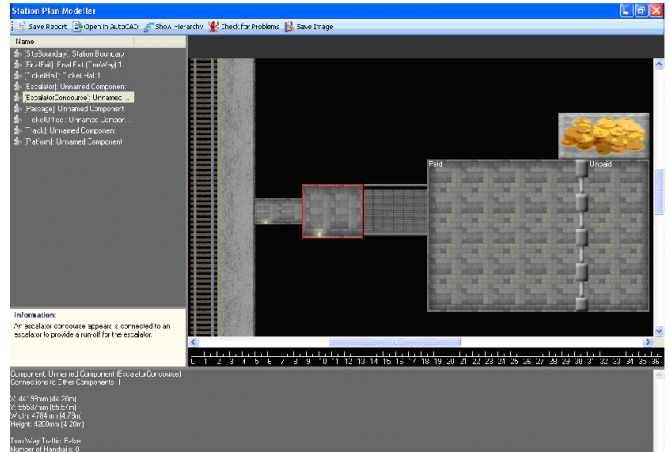


Figure 10 – Layout Module Graphical User Interface Screen

Figure 10 shows the 'Layout' module screen itself. Detailed component information such as its relative position in the site layout and its absolute sizing is displayed in the bottom screen of the interface when the component is selected from the vocabulary list on the left side of the screen. A scale bar, using metres, is located at the base of the interactive design environment to support the designer with visualising spatial proportionality.

Permanent Way (railway track) is inserted independently of the ticket hall, and it may be inserted horizontally or vertically to suit the site conditions.

A summary screen, accessed off the 'Expert Knowledge' module interface, collates all specified components in each generated layout. This screen lists all components from passenger, non-passenger and ancillary categories, with the widths of infrastructure also summarised for the design team's perusal. The SGEvac summary screen allows the designer to input this important data for assessing evacuation times.

The SGEvac 'show hierarchy' function shown in Figure 11 places connecting lines between station elements in the order they have been added. This serves as a safeguard against deleting components out of sequence that could lead to an invalid solution by manual override of the SGEvac rule scheduling [20].

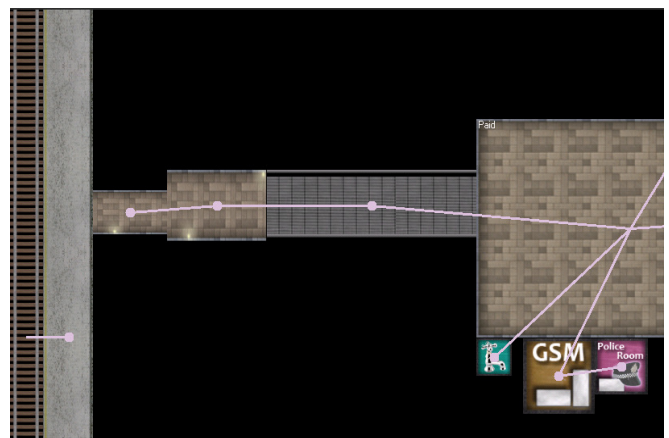


Figure 11 – SGEvac Hierarchy Function

VII. SGEVAC TESTING & VALIDATION

The SGEvac layouts are validated against code requirements via the SP5G5 Hand Calculation method and via extensive fire evacuation simulations, using *Simulex*. The *Simulex* programme, which has undergone its own rigorous validation [21], aids modelling people movement to assess whether evacuation times have improved via the shape grammar approach.

Profile characteristics and type of passengers are entered into the program to ensure realistic evacuation scenarios are executed. The fastest route scenario or exit via the nearest point may not allow accurate conclusions to be drawn, given results from previous human behavioural studies [22]. Thus, our model has control over occupant parameters, allowing the designer to bring expert knowledge to the validation strategy.

In this example part of the station (see Figure 12), the track and platform are set to the left, with two escape passages located within 20m of the platform edge to meet the requirements of LU travelling distances. The location of the central passage from the platform that links to the stair also meets compliant travelling distance requirements.

The stair is created due to the level difference between the platform and ticket hall being between 0.5 and 5m and suitable passenger numbers, as specified in SP5G5. A stair also connects the ticket hall to a passage that leads to a final exit.

The generated layouts, such as that shown in Figure 12 are then exported to *Simulex*, creating test run as shown in Figure 13. The test run was populated with 400 passengers on the platform, with passengers modelled as commuters with no pre-movement time.

Figure 14 shows an example of the evacuation at the 60 seconds time interval.

The platform was evacuated in 1 minute and 16 seconds. Exit 1 was cleared in 3 minutes and 57 seconds. Passengers were all out of the ticket hall at 3 minutes and 21 seconds and the clearance of Exit 2 and the whole station occurred at 5 minutes and 32 seconds.

This test run demonstrates SGEvac capability to automatically generate layouts that meet the London Underground four minute platform clearance time and the six minute target time to a place of safety. Furthermore, SGEvac helps the design team by accurate sizing of infrastructure too, so that much of calculations are already achieved in the design of the shape grammar rules. Architectural and engineering minds can therefore concentrate on the multiple layouts comparison and other qualitative design tasks that will add value to the station design and its effective evacuation.

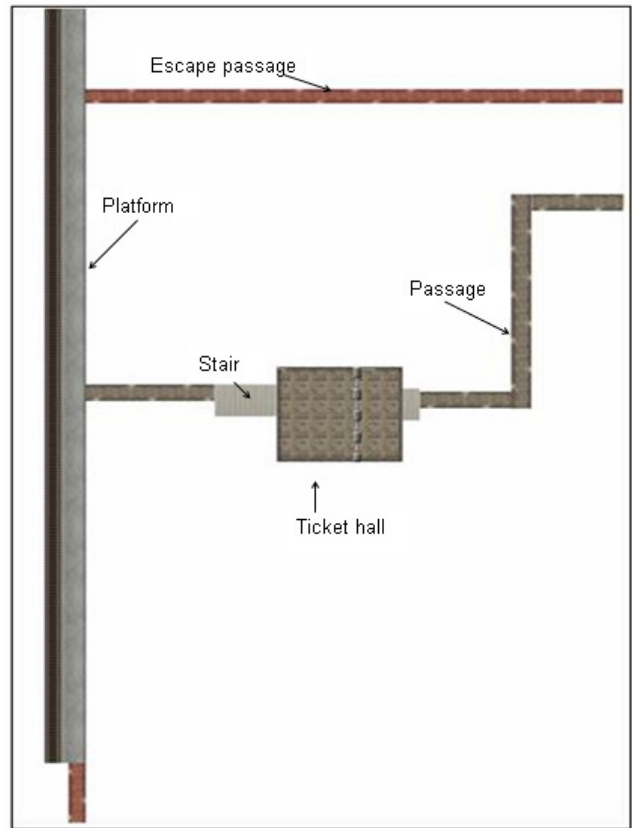


Figure 12 – SGEvac Automatically Generated Layout

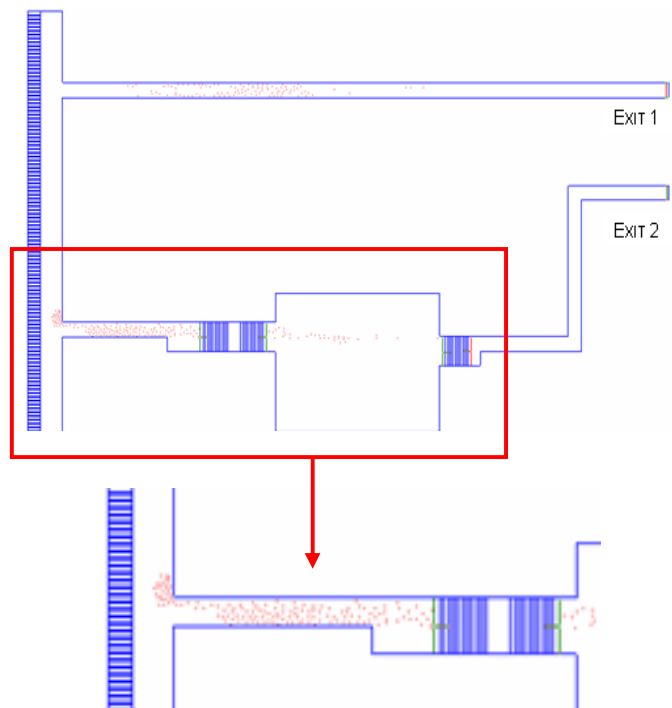


Figure 13 – Simulex Test Run at 60 seconds

VIII. FUTURE WORK

The fire safety strategy in terms of performance based fire risk design is an important aspect of future research. Liaison with experts to determine how such varied criteria could be allied with layout planning should be investigated and implemented. This would lead to further development of the expert knowledge database on an on-going basis in light of changes to legislation. International legislative database interfaces could be developed, with SGEvac able to select the applicable body of knowledge (made easier by the existence of two global standards in NFPA130 [23] and BOStrab [24]) and integrate them with shape grammar rules.

Site constraint issues would also benefit from future development, as well as a move towards development of a three-dimensional SGEvac version. Once devised, other relevant 3D modelling systems, such as computational fluid dynamics (CFD) smoke movement software could be utilised in conjunction with SGEvac, broadening the shape grammar system into other fire safety aspects other than evacuation studies.

IX. CONCLUSIONS

A finite set of station infrastructure components and a finite set of connection possibilities allow for increasingly complex composite shapes to be automatically produced, some of which are credible station layouts at 'reference' block plan level. The SGEvac system under development carefully considers London Underground Station Planning Standards and Guidelines (SPSG5 2007), translating the stipulated parameters into shape grammar rules. This has led to a restrictive, additive grammar being considered appropriate for SGEvac, driven by peak passenger flow data, site boundaries and vertical interchange levels between landmark areas in the station complex.

The rules themselves are directed towards improving evacuation times scrutinised by designers in the BS 7974 fire safety engineering process. The grammar has been developed using a generic logic model method, with each of the six steps of the logic model methodology appraised in this paper. The process has also been aligned to performance based FSE.

The major benefit to the design team is in the review of accurately sized and correctly placed infrastructure over several design iterations at the reference or conceptual stage of the station layout planning process. Efficiencies are gained with respect to option appraisals and quantitative testing. Multiple options made available for preliminary discussions with regulating bodies such as the London Fire Brigade will aid dialogue and help designers to reach an effective end result.

Use of evacuation software such as *Simulex* should lead to more effective layouts in relation to means of escape, travelling distances and improvement in the total evacuation times. Potential layout improvements could not only benefit evacuation situations, but also enhance the through-flow of passengers during normal 'rush hour' periods.

Metro systems are becoming increasingly popular for urban transportation solutions across the world, and so the portability of SGEvac is perceived as an important aspect, respectful of

redevelopment that will be required to adapt to other countries design legislation.

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