Procedural content generation of virtual terrain for games

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Abstract

Game developers use Procedural Content Generation (PCG) in aid of game development to reduce costs, reach better memory consumption, increase creativity, and augment our limited human imagination by generating content algorithmically. Virtual terrain is one of the main topics of PCG; how well do these techniques support the special needs of game level design? To answer this question, a literature review was conducted to analyse correlation between the capabilities of various PCG-techniques and the needs of level design patterns. We observed that techniques permitting higher degree of local control increased their applicability for virtual terrain in games and that traditional fractal techniques, such as the midpoint displacement method and noise-functions, performed poorly despite their popularity. Our foremost contributions to this field of study were new insights towards more suitable PCG-techniques for use in game development.

Keywords
Games, Game Design, Design Patterns, Level Design, Procedural Content Generation, Procedural Terrain Generation, Virtual Worlds

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1. Contents

2. Introduction

According to the Interactive Software Federation of Europe (ISFE) (2021), video games represent one of the most compelling economic successes in Europe and are a rapidly growing segment of the creative industries. The video games industry in Europe and UK is worth approximately 23.3 billion euros in total and the revenue of the industry is growing each year including a large growth of 22% in the year 2020 (ISFE, 2021). Amongst the many successful titles, many game projects fail to meet the cost of development. This is partially due to the high amount of content such as audio, video, models, and textures necessary for games that all require special expertise and development time to create. With Procedural Content Generation (PCG) the development team can reduce the time and manual labour required to enrich their games with interesting content for the players to enjoy.

Virtual terrain is one of the most notable pieces of content one can find within games. In large open-world games such as Skyrim, developed by Bethesda, there exist vast natural environments for the player to explore and lose themselves in, many of which are far too large to handcraft. Constructing worlds for games is a job extensive enough to warrant the existence of specialized level designers who, much like the architects and environmental engineers constructing our living world, oversee building of the game space. Fortunately, generation of terrain is one of the many problems that PCG has solved in a variety of ways, but to what standard? Many considerations are taken when crafting game worlds for an enjoyable player experience and the savings made with Procedural Terrain Generation (PTG) shouldn't come at the expense of quality.

Inspired by this quality-efficiency balance the purpose of this study is to review both well-established and novel PTG-techniques in the light of level design. The question we aimed to answer goes as follows: what makes PTG-techniques suitable for generating virtual terrain for games? The problem is divided into two sub questions. Firstly, what are the capabilities of existing PTG-techniques? Secondly, what kind of terrain features are needed in virtual terrain for games? These questions were answered through the means of a literature review.

Common features of PTG-techniques that increased their applicability for generation of virtual terrain for games were identified. Common shortcomings that reduced applicability were also noted. Coverage of a group of level design patterns was evaluated, and least answered needs were outlined. Lastly, future recommendations for study were formulated to improve suitability of PTG-techniques for virtual terrain in games.

The remaining pages of this thesis are structured as follows. Section three introduces the key concepts related to the topic through prior research. In section four, level design patterns for games and PTG-techniques are summarized and brought together through common terrain features. Section five outlines the main findings of the study and provides explicit answers to the stated research questions. Lastly, section six concludes the thesis with summarized results, limitations of the study, and recommendations for further study.

3. Background

In this section the core concepts related to the research topic are walked through based on prior literature. Terms are defined in the way that most supports the context of the study defined by virtual terrain in games, what makes terrain suitable for games, and how it can be made algorithmically to a high standard.

3.1 Virtual terrain

Virtual terrain is most represented by even height-maps consisting of vertices storing elevation values (Hendrikx, Meijer, Van Der Velden, & Iosup, 2013; Raffe, Zambetta, & Li, 2012; Togelius, Yannakakis, Stanley, & Browne, 2011; Gao, & Zhu, 2022; Smelik, Tutenel, Bidarra, & Benes, 2014). They can be loosely defined as two or two-and-a-half dimensional planes (Togelius et al, 2011). Outdoor maps or terrain may constitute the game space that is a term to describe the area in which the game takes place (Hendrix et al, 2013). Terrain features and character are influenced by gameplay (Togelius et al, 2011) and the genre of the game (Raffe et al, 2012). Forward, virtual terrain refers to a height map representing elevation values that can be used to render a model of a landscape.

3.2 Game design patterns

There is a need for common language to talk about games when designing (Björk, Halopainen & Lundgren, 2003; Kreimeier, 2002; Hullett & Whitehead, 2010) and analysing (Björk et al, 2003) games. Currently genres are the most common way to give product information about computer games, however they strongly depend on the popularity of various games (Björk et al, 2003). Hullett and Whitehead (2010) suggest that presently there is no structured way for experienced game level designers to pass on their knowledge. Each designer relies on their own knowledge of existing games, intuitive feel as well as imitation and adoption of elements in existing work.

Kreimeier (2002) was amongst the first to present the idea of design patterns in aid of game design. He sees that Alexandrian design patterns are suitable for use in game development because of their intuitiveness, good documentation, familiarity to software developers, and flexibility. Design patterns in general are applicable to areas, where rigorously formal methods are out of question, such as in creative work. Design patterns are a way to describe player interaction (Björk et al, 2003) and to codify design knowledge or practices (Björk et al, 2003; Hullett and Whitehead, 2010).

Traditionally design patterns are described as problem-solution pairs (Kreimeier, 2002; Björk et al, 2003). Alexandrian patterns offer reusable solutions to recurring problems with a combination of a problem statement and a solution proposal as the key elements (Kreimeier, 2002). Björk et al (2003) challenge this problem-oriented nature of design patterns, stating that not all aspects of design can or should be seen as problem solving. Their refined pattern template contains a name, a description, consequences, a description of how to use the pattern and its relations to other patterns.

From here on, it is enough for design patterns to be understood as pieces of design knowledge formulated as repeatable patterns that describe the intended effect on gameplay and how it can be applied.

3.3 Procedural content generation

Procedural content generation (PCG) refers to the process of generating content automatically and algorithmically instead of manually by human designers (Hendrikx et al, 2013; Togelius et al, 2011; Gao & Zhu, 2022). Manual creation of vast complex worlds in a limited amount of time is expensive and a large burden on the content designers (Hendrikx et al, 2013; Togelius et al, 2011). This automatic generation process is typically still guided by the designers through control parameters or seeds (Togelius et al, 2011; Hendrikx et al, 2013) but is often partially random (Togelius et al, 2011).

Many of the characteristics of PCG make it especially attractive for use in game development (Togelius et al, 2011; Gao & Zhu, 2022). Developers can reach better memory consumption through compression of content that games contain in abundance (Togelius et al, 2011). PCG can also increase creativity by allowing for completely new types of games and augmenting our limited human imagination (Togelius et al, 2011).

3.4 Procedural terrain generation

Terrain generation is one of the main topics of PCG (Gao & Zhu, 2022). According to Raffe et al (2012) most existing research is devoted to the creation of vast landscapes too large to be produced manually resulting in some powerful commercial tools such as Terragen (Planetside Software) capable of producing renderings of photographic terrain. With Procedural Terrain Generation (PTG) game developers can cater to players who enjoy exploration by providing them with large terrains to play on (Raffe et al, 2012.) The most common PTG-techniques provide little control over the generation process and its results (Raffe et al, 2012), but recently there has been a push towards techniques with increased control (Raffe et al, 2012; Hendrikx et al, 2013).

4. Findings

In this section features of virtual terrain in games and a range of PTG-techniques are introduced and mapped together based on the correlation of needs and capabilities. The needs of virtual terrain in games are extracted from related design patterns and the features of the PTG-techniques are briefly summarized to describe their generative capabilities. Lastly, these findings are mapped together in order to draw a picture of the correlation between the two.

4.1 Features of game terrain

Level design patterns are a subgroup of design patters concerned with the characteristics of the game world and how it affects the overall design of the game. Implementing these patterns affect both the features of the terrain and its residing artefacts such as vegetation, roads, signs et cetera. This is the group of design patterns that were relevant for the evaluation of PTG-techniques. The patterns used in the evaluation were retrieved from an online collection with multiple contributors, moderated by Steffan Björk and Jussi Halopainen ("Level Design Patterns", 2010).

Each pattern in the collection was reviewed to collect patterns related to terrain instead of separate world artefacts alone. Patterns were included when they were believed, based on individual experience, to involve terrain features in one or more plausible implementations. A total of 46 level design patterns were inspected out of which 29 were found suitable based on their description. The remaining patterns were either not likely to be natural objects, abstract, or umbrella terms for other more specific patterns.

Numerous patterns were tools to guide player movement in the world. Multiple types of *Transport Routes* were described as separate patterns with differences in accessibility, direction of travel, surroundings, relation to other routes, and relevance to strategic gameplay (*Backtracking Levels*, *Choke Points*, *Conditional Passageways*, *Flanking Routes*, *Laning*, *One-way Travel*, *Vehicle Sections*). *Transport Routes* describe sections in the game world through which players may move to reach important locations. For example, *Choke Points* describe paths that funnel the moving group of players to an opposing group of players in an orderly fashion allowing the opposing team to dominate them through greater angle of attack in player-versus-player (PvP) games. The reverse side of guiding player movement is restricting passage through certain parts of the world making them *Inaccessible Areas*. This can be achieved through tangible objects or otherwise hazardous features (*Environmental Effects*, *Obstacles*, *Traps*). For instance, *Environmental Effects* describe areas that bring variety to gameplay through local effects. If the local effect is negative, such as burning in a pool of lava, it will discourage or prohibit movement. Lastly, few patterns described solutions to aid and encourage *Game World Navigation* which describes the player's attempt to find their way within the game world (*Landmarks*, *Secret Areas*, *Traces*). *Landmarks* for example, are typically large and distinct features for good recognition.

Another popular problem of the patterns was enabling strategic gameplay which is often associated with the presence of opposing forces such as teams of players in PvP games. *Strategic Locations* is a collection of locations in the game world which are advantageous for players to control or have access to (*Arenas*, *Galleries*, *Hiding Places*, *Resource Locations*, *Sniper Locations*, *Strongholds*). For example, *Arenas* are open but constrained areas that naturally or by design become battlegrounds.

Some patterns described a problem most closely related to the configuration of the game world (*Levels*, *Procedurally Generated Game Worlds*, *Reconfigurable Game Worlds*, *Shrinking Game Worlds*, *Territories*, *Tiles*). There was an explicit need for the world to be configured in some suitable way that supports the implementation. To exemplify, the *Levels* pattern describes that the gameplay should be split into portions. From the game space point of view this can mean multiple physically separated sections of the game world or one large world with conditional passageways.

Two of the patterns offered answers to needs that are purely visual. *Illusion of Open Space* is the inclusion of parts in the game world that can be perceived but never entered to represent the game space as larger than it really is. There are also visual considerations regarding *Spawn Points* to preserve thematic consistency. *Spawn Points* are locations where new game objects are brought into the world, in other words spawned. It is often desirable to conceal abrupt appearances of new objects in inaccessible or concealed areas when there is no thematic explanation for the event. For example, in games with the presence of magic, a necromancer would logically be able to summon or spawn new undead character units in a graveyard. If there was no necromancer and no elements of magic, a zombie popping into existence in plain sight would break the immersion.

Lastly, one pattern with a narrative aspect by the name of *Big Dumb Objects* was included. *Big dumb objects* are large artificial objects in game worlds hinting at the existence of greater entities or groups of individuals. One can think of a few potential approaches to implementing these objects in terrain such as unnatural dig sites and tunnels hinting at mining operations by some corporation.

4.2 Overview of PTG-techniques

In this section various new and upcoming as well as old and solidified PTG-techniques are introduced and a short description of each is provided. Included techniques are not limited to ones that have previously been utilized in game development. It is worth a mention that many of the techniques discussed here are novel and still in the form of prototype implementations. For a more holistic view the currently well-established techniques are included to gain new insights about their operability with the level design patterns regardless of their demonstrated use in games today.

4.2.1 Spatial algorithms

Fournier, Fussell, and Carpenter (1982) developed an approximation of fractional Brownian motion (fBm) for the purpose of stochastic computer models such as terrain. The computations are visually satisfactory approximations of fBm in faster time than exact calculations (Fournier et al, 1982.) This method is commonly known as the midpoint displacement method or the diamond-square algorithm.

Smelik et al (2014) discuss noise functions and their use in height map generation. There are many flavors of noise, including Perlin noise (Perlin, 1985), suitable for features such as ridges or rolling hills. Summing several octaves of noise of increasing frequency results in natural mountainous structures. Terrains provided by noise generators are often homogeneous with no local variation of features.

Kamal and Uddin (2007) developed a parametrically controlled artificial terrain generation system focusing on the problem of landscapes with a primary mountain or crater at a certain location. Features such as height (depth), spread of the base region and degree of irregularity can be controlled. The future of this technique could involve generation of multiple parametrically controlled mountains in a single landscape.

Emmanuel, Mathuram, Priyadarshi, George and Anitha (2019) describe Voronoi Tessellation as a natural phenomenon which happens in the valleys where mountains meet. Regions are represented by a set of all points closest to that centre of a region. Raising mountains while lifting the surrounding terrain results in Voronoi Tessellation. However, this results in very cartoonish hills with no ruggedness which can be corrected using other methods such as Perlin noise or midpoint displacement method.

4.2.2 Search-based techniques

Frade, Vega, and Cotta (2010) developed a technique they call Genetic Terrain Programming (GenTP) to automatically evolve Terrain Programs (TPs) which can generate terrains procedurally. The technique is demonstrated through its integration on the Chapas video game. GenTP performs evaluation of the TPs based on accessibility parameters which control the slope threshold differentiating accessible and inaccessible areas and how much area should be accessible. Further research is needed to achieve a wider range of real looking terrain types.

Togelius, Preuss, and Yannakis (2010) developed a technique for generating maps for real-time strategy (RTS) games. The generated maps are evaluated on multiple objectives promoting fairness, interestingness, playability, and aesthetics. The direct representation of the generated maps contains a mountainous heightmap and additional base and resource location information. While the generated maps look like plausible and playable RTS maps, this is only the first step towards multi-objective search-based PCG for RTS maps and a number of issues remain unexplored.

Ashlock, Gent, and Bryden (2005) developed an evolvable midpoint Lindenmayer-system (L-system) to generate rugged versions of idealized smooth landscapes. The system is like the midpoint displacement method except it is deterministic allowing for fixed complex shapes. Each system is evolved to fit a specified landscape. The system is tested to work well on hills and sufficiently well on crater landscapes.

Raffe, Zambetta, and Li (2011) developed an evolutionary patch-based terrain generation system. Patches are sampled from provided example height-maps and stitched together to create new larger height maps. The user controls the generation process through two-phased interactive evolution. The terrain is appropriate for use in video games due to rich features and high connectivity.

4.2.3 Erosion

Musgrave, Kolb, and Mace (1989) modelled two distinct physical erosion models: hydraulic erosion and thermal weathering. Hydraulic erosion is caused by running water carrying soil from higher points to lower areas and thermal weathering refers to the non-hydraulic process in which rock flakes off steep inclines forming talus slopes at the base. The effects of the models on the subject terrain can be seen, for example, in the formation of streams, gullies, confluences, alluvial fans, talus slopes and dunes.

4.2.4 Complex systems

Doran and Parberry (2010) prototyped a terrain generation technique based on software agents. Autonomous agents run in three phases creating coastline, landforms and erosion conforming with the user constraints. The prototype employs agents which create coastline, smooth areas, beaches, mountains, and rivers, but more agent types can be implemented. The number of terrain features can be controlled alongside few other qualities about them.

4.2.5 Sketch-based

Saunders (2006) developed a terrain synthesis technique based on genetic algorithms: Terrainosaurus. The desired terrain is sketched in polygons depicting various terrain types. The sketch lines are distorted, and areas are generated based on user provided example height maps typically from real-world geographic information sources. The resulting height field contains patches of different terrain types from the provided examples (Saunders, 2006.)

Belhadj (2007) presents a fractal-based algorithm to generate fast and highly controllable height maps. Local elevation points can be constrained through elevations obtained from satellites or user sketches.

Gain, Marais, and Straßer (2009) developed Terrain Sketching, an interactive terrain generation system with a sketching interface providing full control over feature placement and properties. The system is able to generate a variety of landforms including steep slopes and indentations. Peaks, cliffs, volcanoes, rolling hills, rivers and canyons can all be created in a single height map when sketched with care.

4.3 Procedural generation of level design patterns

To examine the correlation between the needs of the level design patterns and the capabilities of the PTG-techniques a few assumptions had to be made. To demonstrate the issue at hand, we can begin by asking; what constitutes an obstacle? A generic obstacle is anything impassable by the player, but this definition alone is too unspecific to point out terrain features that create obstacles. Some common assumptions that we placed for rules of a game were the following.

- There exists a force of gravity.
- Under normal circumstances the player is unable to traverse up steep inclines and bodies of water.
- The game is played in the first-person perspective.
- There exists a global sea level.

Now we may state that an obstacle is either a body of water or a steep incline such as a mountain. Similarly, a deep pit could constitute a trap. The assumption of first-person perspective allowed us to answer questions concerned with line-of-sight, such as: what constitutes a hiding place? Global sea level describes a common technique in virtual worlds where a height map is interpreted to contain bodies of water uniformly below a certain height value. Bodies of water were determined to enable many of the level design patterns and were assumed part of the hypothetical game rules for this reason.

The results were collected in a table which due to its large size is included as an appendix at the end of the thesis (Appendix A). Techniques in the first row are referred to by their popular names or by the names of the authors' if one was not appointed to it. The names of the level design patterns in the first column are worded as they were in the online collection. The second column contains a generalization of the terrain features associated with each pattern. The third column additionally lists a few examples of plausible terrain features that could be used to instantiate each pattern. In the remaining columns, suitability of each PTG-technique is assessed for each pattern. Cells containing suitability evaluations are color coded to reflect the results. Green, yellow and red in this order indicate the following: at least one reliable way to instantiate the pattern had been thought of using one's own judgement, the pattern could be instantiated by chance or reliably after author's planned modifications, and complete misfit. This categorization was also used to score applicability of each technique and coverage of each pattern readable from the last row and column.

5. Discussion

In this section we will take a closer look at the gathered data and present the results that answer the research question at hand. Features that increased or decreased a technique's applicability for virtual terrain in games are outlined and the presently unresolved challenges of level design are laid out. Additionally, the PTG-techniques are matched with existing knowledge on desired features of PCG in games.

It is important to recite that there isn't one correct way to implement a level design pattern and not all should be implemented through terrain features, even when it's possible to do so. There may exist simple solutions besides implementation through terrain and many terrain implementations were likely to be overlooked in the process. This means that the results of our work are indicative rather than absolute truths.

5.1 Capabilities of PTG-techniques

The academic research looks to be heavily focused on the generation of life-like realistic virtual terrain. While realistic terrain has its applications in games it is not the only artistic choice for virtual worlds found within them. Games do not strictly need to adhere to terrain features present in the real world. Successful commercial games such as Monster Hunter World, developed by Capcom, invite the player to a large alien world inspired but not limited by the nature we know.

Not all techniques were created equal. Some were intended for limited use cases, and some still prototypes with limited functionality. A few approaches couldn't generate terrain on their own and required input terrain to get started. Such limitations were accounted for by acknowledging future development plans of the authors and through assumptions regarding the setup in which the generation takes place.

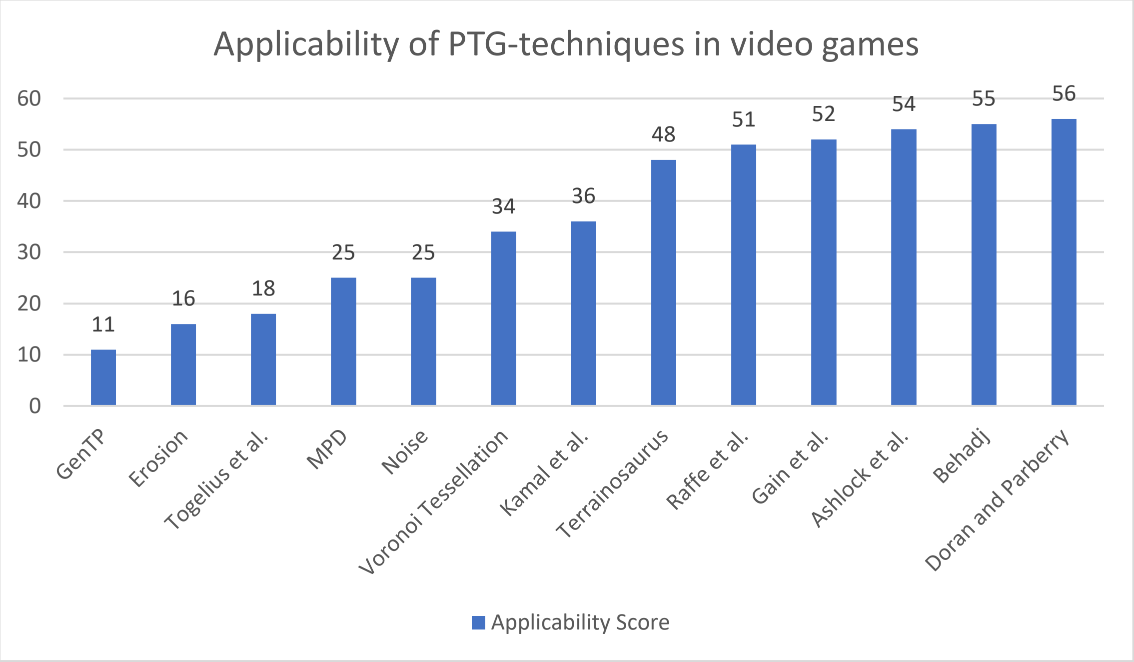

Figure 1. Applicability of PTG-techniques in video games.

Figure 1 shows the assessment of applicability of various PTG-techniques in video games. The applicability score is a sum of the technique's evaluated ability to instantiate each of the individual level design patterns. A maximum score of 58 could be reached if the technique was assessed to reliably provide a way to instantiate all of the patterns.

GenTP suffered from high homogeneity and low feature diversity of the terrain that solely consisted of soft rolling hills. In this context, diversity refers to the technique's ability to provide a variety of terrain features. Clearly, the combination of these two characteristics results in a repetitive landscape with very limited support for a wide range of design patterns.

Erosion scored low because it seemed to have little use in games from a functional standpoint. It may improve traversability of terrain through its smoothing capabilities which is important for patterns concerned with player movement but will not reliably create pattern enabling features from any input terrain. Erosion simulation, particularly hydraulic erosion, can also create waterways that can be useful for a few design patterns.

The technique of Togelius et al. was not favored in this general evaluation possibly due to its high specialization in RTS maps. If the evaluation had only included patterns related to ones commonly present in games of this genre, it would likely have performed better.

Fractal MPD and noise techniques, which one might consider the baseline of the evaluation due to their popularity, did also not score very high. Both techniques allow for very low amount of control apart from parameters with global effects resulting in homogeneous terrain of mountains and soft rolling hills. Multiple flavors of noise using different noise algorithms may improve its case, but the issues of homogeneity and low degree of local control remain.

A step-up in applicability through control over feature placement and properties could be observed in two techniques. Voronoi tessellation, albeit resulting in crudely polished smooth peaks, could plausibly form paths and areas when the height and center of the peaks are controllable. The technique of Kamal et al. could, if expanded to support placement of multiple features, do the same and more in an aesthetically pleasing manner.

Six most applicable techniques of the evaluation allowed the designer to control both feature placement and properties with the added benefit of high feature diversity. Multiple approaches for diversity were observed: sketch input, use of sample and example terrain, and the use of multiple different procedures.

5.2 Needs of game level design

When gathering sources for this thesis it became apparent that not many game design pattern collections were readily available. A few authors had created a collection based on their research, but the provided website had since broken, or it had been taken down. Without knowing the true popularity of level design pattern use in the games industry, it was possible that a collection had not yet emerged to enjoy wide popularity among the designers.

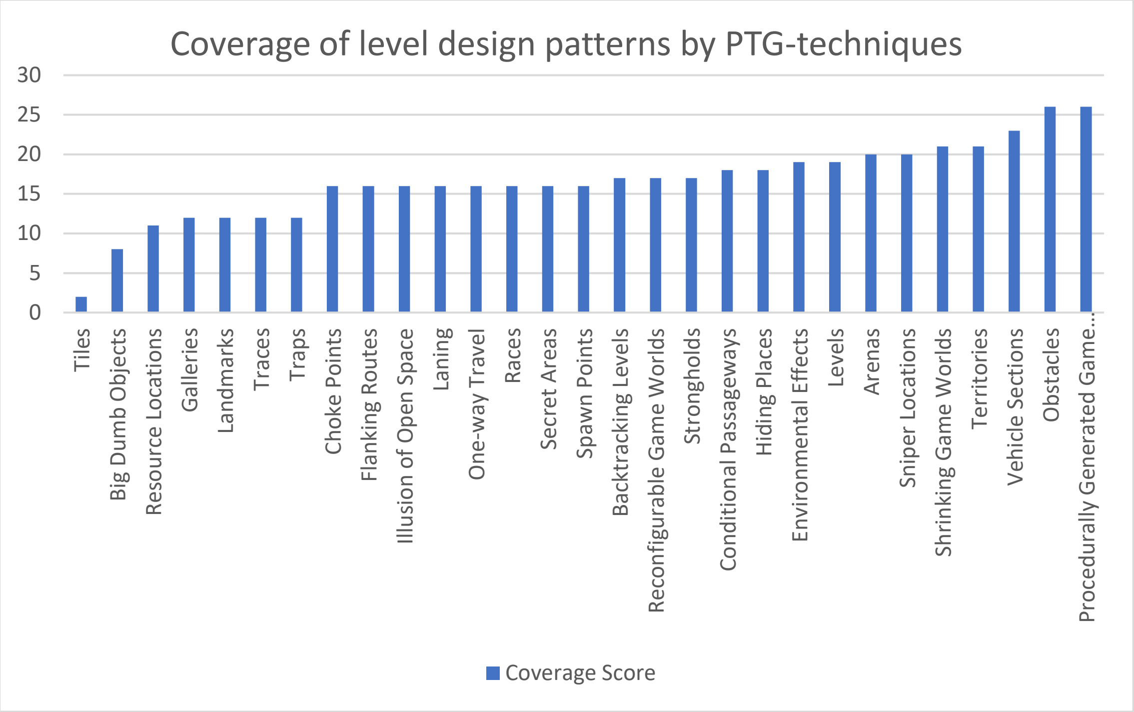

Figure 2. Coverage of level design patterns by PTG-techniques

Figure 2 shows the assessment of coverage of various level design patterns by the PTG-techniques included in the study. The coverage score is a sum of the pattern's evaluated possibility to be instantiated by each of the individual PTG-techniques. A maximum score of 26 could be reached if each of the techniques were assessed to reliably provide a way to instantiate the pattern.

A common aspect of many of the least covered patterns scoring 12 or less was the requirement of the feature standing out visually. This finding aligned well with the least applicable PTG-techniques suffering from homogeneity and low diversity of output terrain. Other aspects of these patterns were a specific structural demand as in the case of *Tiles*, high complexity as in the case of *Galleries* and limited terrain solutions as in the case of *Traps*. Only the technique of Raffe et al. employed patch-based generation. High complexity of a required feature makes it rare if not impossible for the specific feature to emerge through procedures employing significant randomness.

The largest number of patterns associated with player movement or line of sight such as various routes, passages, and areas with no requirement of uniqueness are mostly answered by PTG-techniques but for them to be reliably and precisely generated controlled feature placement was deemed necessary. For example, fractal terrain generated through MPD or Noise has a chance to result in natural valleys suitable for *Arenas* but without any guarantees. The more extensive the demands of a pattern were, the less likely it was evaluated to occur by chance in less controlled generation.

A few patterns enjoyed high coverage because they could plausibly exist with the presence of water such as any beds of water for *Vehicle sections*, *Environmental effects* or *Conditional passageways*, and islands within a sea for *Territories*, *Levels*, or *Illusion of open space*. Establishing these patterns in other ways may be more challenging.

All techniques could instantiate *Obstacles* as they are fundamentally easy to establish with practically any height differences rougher than soft rolling hills. Same goes for

Procedurally generated game worlds that raised a trivial question of whether PTG-techniques are suitable to procedurally generate content for game worlds.

5.3 Suitability of PTG-techniques for games

It has been indicated that the recent push for increased control in PCG-techniques is warranted when it comes to PTG in games. Controlled feature placement and -properties looked to improve technique suitability for virtual terrain in games, through instantiation of level design patterns. Sketch- and search-based techniques were especially useful in asserting control over the generation process. However, as increased creativity and augmentation of human imagination is seen as one of the appealing characteristics of PCG in games, there may be better or worse ways to affect the generation results. Sketch-based and search-based methods that work towards idealized terrain could trump on the technique's ability to aid innovation and be merely the means to reach beautiful results for an already solved problem.

A couple of alternative approaches to increase control without imposing a strict terrain layout were found in the techniques of Raffe et al. and Doran and Parberry. The search-based technique of Raffe et al. allowed the designer to control the direction of evolution from an initially random configuration of sample terrain patches. Doran and Parberry's technique on the other hand permitted the designer to control quantities and properties of desired features for the system to assemble in a chaotic manner. Both techniques allowed the designer to assert high degree of control in some aspects of the generation but provided emergent results of randomness for the rest. These techniques may be seen as more suitable for game designers when innovation is valued higher than strict precision.

A problem that PCG is commonly directed at is the expense of manually crafting content for games and the burden it places on the designers. As it has been discussed, the rules of the game dictate the requirements of the used terrain. Only a selection of level design patterns would exist in a single game and rules of player movement play a significant role in what constitutes inaccessible areas et cetera. It is beneficial to understand that increased control at the cost of sketching, interactive evolution, or implementation of complex procedures may be unnecessary, if traditional unconstrained fractal terrain is more than suitable.

6. Conclusions

We found that controlled feature placement, controlled feature properties and sufficient feature diversity are all important features of PTG-techniques used for the generation of virtual terrain for games. High degree of local control was indicated especially useful for clearly splitting the impassable and traversable area to control player movement. For ease of navigation and recognition of key gameplay locations it was important to provide enough visually distinct features through variety.

Features of PTG-techniques that were deemed harmful for their use in game development were homogeneity, low degree of local control and low feature diversity. Using techniques suffering from the first two problems it was largely unreliable to direct player movement and design strategic gameplay areas. Additionally, low feature diversity would potentially make terrain difficult to navigate by the players.

These results have further indicated that the recent push for increased control for PCG-techniques is warranted in the context of game terrain. However, many of the newer techniques raised concern for loss of innovative capability including ones that rely on sketches or idealized terrain for input. It may be more interesting to pursue alternative approaches to maintain a reasonable balance between control and unpredictability such as the ones demonstrated in the techniques of Raffe et al. and Doran and Parberry.

Some notable limitations applied to this study. The PTG-techniques were only inspected for their generative capabilities ignoring other benefits or drawbacks that are vital for choosing the most suitable technique in practice. Examples of such characteristics include computational expense, data compression, visual appeal, and speed. Additionally, some very novel techniques were excluded for their immaturity. New ideas emerging from the fields of machine learning and deep learning were especially uncharted for terrain generation. Lastly, many of the newer introduced techniques have not been demonstrated in practice.

Finally, based on our findings here are a few recommendations for further study to improve the case for PCG in terrain generation for games.

- Use of player movement information in generation of terrain.
- Implementation of key gameplay locations for the system of Doran and Parberry or other similar system.

Because player movement is a common problem in level design, it could be beneficial to find solutions to incorporate player movement information into a PTG-system. Such a system would be able to differentiate between impassable and traversable area without imposing arbitrary rules and assumptions. Doran and Parberry’s system was seen as one of the most appealing techniques for its control and flexibility and it would be interesting to see it adapted for some type of a game to confirm its potential.

7. References

1. Ashlock, D. A., Gent, S. P., & Bryden, K. M. (2005, September). Evolution of l-systems for compact virtual landscape generation. In *2005 IEEE Congress on Evolutionary Computation* (Vol. 3, pp. 2760-2767). IEEE.
2. Belhadj, F. (2007, October). Terrain modeling: a constrained fractal model. In *Proceedings of the 5th international conference on Computer graphics, virtual reality, visualisation and interaction in Africa* (pp. 197-204).
3. Björk, S., Halopainen, H., Lundgren, S. (2003). 15. Game Design Patterns. In *Level Up: Digital Games Research Conference*, 4-6 November, 2003, Utrecht University. Faculty of Arts, Utrecht University.
4. Doran, J., & Parberry, I. (2010). Controlled procedural terrain generation using software agents. *IEEE Transactions on Computational Intelligence and AI in Games*, *2*(2), 111-119.
5. Emmanuel, K. S., Mathuram, C., Priyadarshi, A. R., George, R. A., & Anitha, J. (2019, March). A Beginners Guide to Procedural Terrain Modelling Techniques. In *2019 2nd International Conference on Signal Processing and Communication (ICSPC)* (pp. 212-217). IEEE.
6. Fournier, A., Fussell, D., & Carpenter, L. (1982). Computer rendering of stochastic models. *Communications of the ACM*, *25*(6), 371-384.
7. Frade, M., Vega, F. F. D., & Cotta, C. (2010, April). Evolution of artificial terrains for video games based on accessibility. In *European Conference on the Applications of Evolutionary Computation* (pp. 90-99). Springer, Berlin, Heidelberg.
8. Gain, J., Marais, P., & Straßer, W. (2009, February). Terrain sketching. In *Proceedings of the 2009 symposium on Interactive 3D graphics and games* (pp. 31-38).
9. Gao, T., & Zhu, J. (2022, February). A Survey of Procedural Content Generation of Natural Objects in Games. In *2022 International Conference on Artificial Intelligence in Information and Communication (ICAIIC)* (pp. 275-279). IEEE.
10. Hendrikx, M., Meijer, S., Van Der Velden, J., & Iosup, A. (2013). Procedural content generation for games: A survey. *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, *9*(1), 1-22.
11. Hullett, K., & Whitehead, J. (2010, June). Design patterns in FPS levels. In *proceedings of the Fifth International Conference on the Foundations of Digital Games* (pp. 78-85).
12. Interactive Software Federation of Europe. (n.d), *Economic success*, Retrieved from https://www.isfe.eu/game-industry/economic-success/
13. Kamal, K. R., & Uddin, Y. S. (2007, December). Parametrically controlled terrain generation. In *Proceedings of the 5th international conference on Computer graphics and interactive techniques in Australia and Southeast Asia* (pp. 17-23).
14. Kreimeier, B. (2002 March 13). The Case For Game Design Patterns. *Game Developer.* Retrieved from https://www.gamedeveloper.com/design/the-case-for-game-design-patterns
15. N.a. (2010 May 2). *Level Design Patterns*. Retrieved from http://virt10.itu.chalmers.se/index.php/Category:Level_Design_Patterns
16. Musgrave, F. K., Kolb, C. E., & Mace, R. S. (1989). The synthesis and rendering of eroded fractal terrains. *ACM Siggraph Computer Graphics*, *23*(3), 41-50.

17. Raffe, W. L., Zambetta, F., & Li, X. (2011, July). Evolving patch-based terrains for use in video games. In *Proceedings of the 13th annual conference on Genetic and evolutionary computation* (pp. 363-370).
18. Raffe, W. L., Zambetta, F., & Li, X. (2012, June). A survey of procedural terrain generation techniques using evolutionary algorithms. In *2012 IEEE Congress on Evolutionary Computation* (pp. 1-8). IEEE.
19. Saunders, R. L. (2007). *Terrainosaurus: realistic terrain synthesis using genetic algorithms* (Doctoral dissertation, Texas A&M University).
20. Smelik, R. M., Tutenel, T., Bidarra, R., & Benes, B. (2014, September). A survey on procedural modelling for virtual worlds. In *Computer Graphics Forum* (Vol. 33, No. 6, pp. 31-50).
21. Togelius, J., Preuss, M., & Yannakakis, G. N. (2010, June). Towards multiobjective procedural map generation. In *Proceedings of the 2010 workshop on procedural content generation in games* (pp. 1-8)
22. Togelius, J., Yannakakis, G. N., Stanley, K. O., & Browne, C. (2011). Search-based procedural content generation: A taxonomy and survey. *IEEE Transactions on Computational Intelligence and AI in Games*, *3*(3), 172-186.

Appendix A. Procedural generation of level design patterns

Pattern name	**Terrain aspect**	**Examples of plausibly suitable terrain features or landscapes**	**Midpoint displacement method**	**Noise functions**	**Kamal et al. (2007)**	**Behadj (2007)**	**Voronoi tessellation**	**GenTP**	**Togelius et al. (2010)**	**Ashlock et al. (2005)**	**Raffe et al. (2011)**	**Physical erosion models: hydraulic erosion and thermal weathering**	**Doran and Parberry (2010)**	**Terrainosaurus**	**Gain et al. (2009)**	**Pattern coverage Green: + 2 Yellow: + 1 Red: + 0**
Arenas	Open but constrained areas.	valleys and plateaus with limited access points	Chance of suitable features.	Chance of suitable features.	Possible if the system is expanded to support placement of multiple features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Chance of suitable features.	Chance of suitable features.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	May aid by smoothing the landscape for better traversability.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**20**
Backtracking levels	Bi-directionally traversable levels with a dead-end.	routes of even elevation to dead ends	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Possible if the system is expanded to support placement of multiple features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Generation of suitable features unlikely.	Chance of suitable features.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	May aid by smoothing the landscape for better traversability.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**17**
Big dumb objects	Outstanding artificial features designed to serve the narrative aspect of the game.	unnatural dig sites, mines, crop fields	Does not generate artificial features.	Does not generate artificial features.	Does not generate artificial features.	Some suitable features can be sketched.	Does not generate artificial features.	Does not generate artificial features.	Does not generate artificial features.	New L-system could be evolved to generate suitable features.	Can be generated if suitable features are present in the source terrain.	Does not generate artificial features.	Specialized agent can be implemented for suitable features.	Chance to be generated if suitable features are present in the source terrain.	Does not generate artificial features.	**8**
Choke points	Narrow sections providing only access to an area.	small routes through a mountain range	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Possible if the system is expanded to support placement of multiple features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Generation of suitable features unlikely.	Chance of suitable features.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**16**
Conditional passageways	Conditional transport routes. Feature depends on the condition.	mountain tops (flight), islands (swimming)	Can generate some suitable features.	Can generate some suitable features.	Can generate some suitable features.	Some suitable features can be sketched.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**18**
Environmental effects	Outstanding features designed to provide local effects. Feature depends on the effect.	lava beds (burn), water beds (drowning)	Can generate some suitable features.	Can generate some suitable features.	Can generate some suitable features.	Some suitable features can be sketched.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Can generate some suitable features.	Specialized agent can be implemented for suitable features.	Chance to be generated if suitable features are present in the source terrain.	Some suitable features can be sketched.	**19**
Flanking routes	Additional less accessible transport routes to an area.	a smaller route among multiple routes	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Possible if the system is expanded to support placement of multiple features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Generation of suitable features unlikely.	Chance of suitable features.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**16**
Galleries	Raised areas overlooking a transport route.	route at the bottom of a chasm	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Some suitable features can be sketched.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**12**
Hiding places	Secret areas or locations with obscured line of sight.	caves, small hills and pits, chasms, mazes	Chance of suitable features.	Chance of suitable features.	Can generate some suitable features.	Some suitable features can be sketched.	Can generate some suitable features.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**18**
Illusion of open space	Inaccessible areas blocked by permanent obstacles.	remote islands, unreachable plateaus	Can generate some suitable features.	Can generate some suitable features.	Generation of suitable features unlikely.	Some suitable features can be sketched.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**16**
Landmarks	Outstanding features designed to aid navigation.	a large crater, the highest mountain, the main river running across the land	Terrain is too homogeneous to produce suitable features.	Terrain is too homogeneous to produce suitable features.	Can generate some suitable features.	Some suitable features can be sketched.	Terrain is too homogeneous to produce suitable features.	Terrain is too homogeneous to produce suitable features.	Terrain is too homogeneous to produce suitable features.	New L-system could be evolved to generate suitable features.	Can be generated if suitable features are present in the source terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Chance to be generated if suitable features are present in the source terrain.	Some suitable features can be sketched.	**12**
Laning	Limited number of alternative transport routes between two locations.	side by side ravines connecting two valleys	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Possible if the system is expanded to support placement of multiple features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Generation of suitable features unlikely.	Chance of suitable features.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**16**
Levels	Physically or mechanically separate areas in the world for sections of gameplay.	separate islands, isolated areas within one continent with limited connectivity	Can generate some suitable features.	Can generate some suitable features.	Possible if the system is expanded to support placement of multiple features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**19**

Pattern name	Terrain aspect	Examples of plausibly suitable terrain features or landscapes	Midpoint displacement method	Noise functions	Kamal et al. (2007)	Behadj (2007)	Voronoi tessellation	GenTP	Togelius et al. (2010)	Ashlock et al. (2005)	Raffe et al. (2011)	Physical erosion models: hydraulic erosion and thermal weathering	Doran and Parberry (2010)	Terrainosaurus	Gain et al. (2009)	Pattern coverage Green: + 2 Yellow: + 1 Red: + 0
Obstacles	Permanently or temporarily impassable features.	steep hills, mountains, water beds	Can generate some suitable features.	Can generate some suitable features.	Can generate some suitable features.	Some suitable features can be sketched.	Can generate some suitable features.	Can generate some suitable features.	Can generate some suitable features.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Can generate some suitable features.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	26
One-way travel	One-way traversable sections of the world.	cliffs, deep pits, chasms	Chance of suitable features.	Chance of suitable features.	Can generate some suitable features.	Some suitable features can be sketched.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	16
Procedurally generated game worlds	Game worlds that are fully or partially procedurally generated.	terrain generated algorithmically	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	26
Races	Terrain designed to be raced.	(looping) route, even soft hill	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Possible if the system is expanded to support placement of multiple features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	May aid by smoothing the landscape for better traversability.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	16
Reconfigurable game worlds	Reconfigurable or regeneratable terrain between instances of play or during play.	rotating land tiles, expanding land on demand	Can generate more landscape on demand. And create unique landscapes.	Can generate more landscape on demand. And create unique landscapes.	Can generate unique landscape between instances.	Can generate more landscape on demand and unique landscapes when unconstrained.	Can generate more landscape on demand. And create unique landscapes.	Can generate unique landscape between instances.	Can generate unique landscape between instances.	Does not generate new or unique landscape autonomously.	Can generate new or unique landscape if evolution is made autonomous.	Does not generate new or unique landscape autonomously.	Can generate unique landscape between instances.	Same sketch and source terrain types can produce varied results.	Does not generate new or unique landscape autonomously.	17
Resource locations	Outstanding features designed to provide resources.	mines, crop fields	Terrain is too homogeneous to produce suitable features.	Terrain is too homogeneous to produce suitable features.	Terrain is too homogeneous to produce suitable features.	Some suitable features can be sketched.	Terrain is too homogeneous to produce suitable features.	Terrain is too homogeneous to produce suitable features.	Plans resource locations but doesn't consider their physical properties.	New L-system could be evolved to generate suitable features.	Can be generated if suitable features are present in the source terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Chance to be generated if suitable features are present in the source terrain.	Some suitable features can be sketched.	11
Secret areas	Areas behind unknown conditional passageways or within obscured line of sight.	small caves, pits, chasms	Chance of suitable features.	Chance of suitable features.	Can generate some suitable features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Can be generated if suitable features are present in the source terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Chance to be generated if suitable features are present in the source terrain.	Some suitable features can be sketched.	16
Shrinking game worlds	Terrain reducible in playable area by making areas inaccessible.	even soft hill, largely traversable rolling hills	Can generate some suitable features.	Can generate some suitable features.	Can generate some suitable features.	Some suitable features can be sketched.	Generation of suitable features unlikely.	Can generate some suitable features.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	May aid by smoothing the landscape for better traversability.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	21
Sniper locations	Higher or visually obscured locations with line of sight to an area.	hills, cliffs, soft pits, plateaus	Chance of suitable features.	Chance of suitable features.	Can generate some suitable features.	Some suitable features can be sketched.	Can generate some suitable features.	Generation of suitable features unlikely.	Can generate some suitable features.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	20
Spawn points	Areas suitable for spawning players or other game objects. Depends on the spawn.	one-way travel exits (player), visually obscured inaccessible areas (enemy)	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Possible if the system is expanded to support placement of multiple features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Generation of suitable features unlikely.	Plans base locations but doesn't consider their physical properties.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	16
Strongholds	Areas with choke points as the only entry points. (Line of sight to nearby areas)	valleys and plateaus with limited access points (within large open fields)	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Possible if the system is expanded to support placement of multiple features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Generation of suitable features unlikely.	Chance of suitable features.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	May aid by smoothing the landscape for better traversability.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	17
Territories	Areas with limited connectivity that can be provisioned and owned.	terrain shattered with rivers, mountainous terrain with limited routes, islands	Can generate some suitable features.	Can generate some suitable features.	Possible if the system is expanded to support placement of multiple features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	Can generate some suitable features.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	21
Tiles	Terrain built from tiles.	terrain made from tileable elements	Not tile-based.	Not tile-based.	Not tile-based.	Not tile-based.	Not tile-based.	Not tile-based.	Not tile-based.	Not tile-based.	Tile-based.	Not tile-based.	Not tile-based.	Not tile-based.	Not tile-based.	2
Traces	Outstanding features designed to guide movement. Depends on target.	small streams (river), peaks of increasing altitude (highest mountain)	Terrain is too homogeneous to produce suitable features.	Terrain is too homogeneous to produce suitable features.	Terrain is too homogeneous to produce suitable features.	Some suitable features can be sketched.	Terrain is too homogeneous to produce suitable features.	Terrain is too homogeneous to produce suitable features.	Terrain is too homogeneous to produce suitable features.	New L-system could be evolved to generate suitable features.	Can be generated if suitable features are present in the source terrain.	Can generate some suitable features.	Specialized agent can be implemented for suitable features.	Chance to be generated if suitable features are present in the source terrain.	Some suitable features can be sketched.	12
Traps	Possibly hidden hazards in the game world.	deep chasms and pits	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Can generate some suitable features.	Some suitable features can be sketched.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	Generation of suitable features unlikely.	New L-system could be evolved to generate suitable features.	Can be generated if suitable features are present in the source terrain.	Generation of suitable features unlikely.	Specialized agent can be implemented for suitable features.	Chance to be generated if suitable features are present in the source terrain.	Some suitable features can be sketched.	12

Pattern name	**Terrain aspect**	**Examples of plausibly suitable terrain features or landscapes**	**Midpoint displacement method**	**Noise functions**	**Kamal et al. (2007)**	**Behadj (2007)**	**Voronoi tessellation**	**GenTP**	**Togelius et al. (2010)**	**Ashlock et al. (2005)**	**Raffe et al. (2011)**	**Physical erosion models: hydraulic erosion and thermal weathering**	**Doran and Parberry (2010)**	**Terrainosaurus**	**Gain et al. (2009)**	**Pattern coverage Green: + 2 Yellow: + 1 Red: + 0**
Vehicle sections	Sections designed to be traversed with vehicles. Depends on the vehicle	water beds (boat), vast flat planes (car), tunnels (train), remote islands (plane)	Can generate some suitable features.	Can generate some suitable features.	Can generate some suitable features.	Some suitable features can be sketched.	Can be generated through careful placement of features.	Can generate some suitable features.	Can generate some suitable features.	New L-system could be evolved to generate suitable features.	Some suitable features can be evolved from typical source terrain e.g. fractal terrain.	May aid by smoothing the landscape for better traversability.	Specialized agent can be implemented for suitable features.	Can be sketched from few typical source terrain types e.g. fractal terrain.	Some suitable features can be sketched.	**23**
Technique applicability Green: + 2 Yellow: + 1 Red: + 0			**25**	**25**	**36**	**55**	**34**	**11**	**18**	**54**	**51**	**16**	**56**	**48**	**52**	