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Exploring Procedural Content Generation of Environments for Virtual Museums: A Mixed-Initiative Approach

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Abstract: Cultural heritage preservation and dissemination face significant challenges in the digital era, particularly in artifact representation, visitor experience personalization, and virtual exploration scalability. This paper presents a tool for the development of a virtual museum, introducing a new system that addresses the challenges of the design and arrangement of the virtual environment process with two integrated stages: (1) Museum Generator, a procedural tool for creating realistic and adaptable virtual museum environments and (2) Artwork Arrangement, an automated system that optimizes the placement of artifacts based on thematic and spatial considerations. The system is validated through a Grid Search Method experiment that seeks to identify the combination of genetic operators that maximizes performance in arranging artworks in a virtual museum and evaluate how modifications to these operators affect the performance of different evolutionary executions. Results indicate that the proposed approach provides an effective and scalable solution for contributing to the design and arrangement of a virtual environment for museums, fostering greater accessibility to cultural heritage and delivering personalized visitor experiences.

Keywords: procedural content generation; genetic algorithms; cultural heritage; virtual museum; mixed initiative

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1. Introduction

1.1. Museum and Interactive Software

Museums serve as vital cultural and educational spaces, preserving historical artifacts and promoting cultural heritage [1,2]. They enhance learning opportunities and foster interaction, discussion, and knowledge exchange about various works [3]. They are essential because they act as custodians of cultural memory, enabling societies to preserve and interpret their heritage across generations. They provide a tangible link to the past, allowing people to engage directly with artifacts that hold historical and cultural significance. This function is especially valuable for fostering social cohesion and collective identity. Furthermore, museums facilitate educational experiences that go beyond textbooks by offering immersive, experiential learning that can adapt to different audiences, thus enhancing the public's understanding and appreciation of culture and history.

In this context, interactive software and virtual experiences have emerged as valuable strategies for promoting cultural heritage [4–6]. By allowing users to interact with simulated environments, communities gain access to specialized knowledge, especially for those who may not have the economic or temporal means to visit physical museums [7–9]. Thus, designing freely accessible digital spaces becomes crucial for disseminating and democratizing cultural heritage, benefiting non-expert and casual users alike [10]. Integrating digital technologies into design strategies can create holistic experiences that connect heritage with the community. Museums play a vital role in enhancing societal well-being by providing opportunities for learning and meaning-making [8]. Virtual museums can further amplify this positive societal impact by making museum collections and educational content available to anyone with an internet connection, regardless of their physical location or ability to visit museums in person. For example, mapping visitor routes enables the adaptation of exhibitions to user preferences, facilitating deeper interactions with art [11]. In addition, fostering dialogue and exchanging interpretations among visitors promotes active appreciation and effective art conservation [12]. Focusing on narratives can improve public understanding and commitment to patrimony [13]. Together, these strategies can lead to life-changing experiences, strengthening the appreciation and protection of cultural heritage through lasting emotional and educational connections [14].

Diverse technologies include computers [15], web-based solutions [16], wall displays [17], tablets [18], mobile devices [19], and augmented reality [5] have been implemented to enhance visitor engagement [20]. For instance, the "Visualising the Victoria" project digitally reconstructed the Victoria Theatre in Newcastle, focusing on improving user experience and usability for individuals with limited mobility [21]. Similarly, a virtual reconstruction of Al-Zubarah, Qatar, utilized data from the Qatar Museums Authority to provide historical insights through a two-stage process involving volumetric modeling and detailed reconstructions of key buildings [22]. Additionally, the Afrasiab Museum in Samarkand, Uzbekistan, employed computer game technologies to allow visitors to explore and interact with 3D replicas of archaeological artifacts, marking the first digital presentation of Afrasiyab's cultural heritage [23]. Virtual museums benefit from technologies such as 360-degree photography [24] and 3D digitization [25], enabling users to engage with virtual elements in a digital narrative [26]. These methods can influence users' perceptions and attitudes towards cultural heritage, thereby impacting their intentions to visit museums [27].

1.2. Challenges in Virtual Museum Development

Designing effective computer simulations for virtual museums involves complex challenges, not only in creating immersive digital spaces but also in achieving cohesive spatial organization. Although virtual experiences allow users to explore various contexts, creating these spaces requires significant time and design expertise. The current research primarily addresses these challenges in isolated aspects, with tools that may focus on layout design, artifact arrangement, or navigation strategies. For example, some studies highlight game-based navigation to enhance spatial cognition, yet these often lack integration with other features like artwork placement or spatial coherence, underscoring the need for more comprehensive, unified workflows [28]. Similarly, tools that focus on virtual accessibility or exhibit design remain modular, addressing single aspects without supporting the complete process of museum creation [29]. This modular approach results in a gap where holistic systems, encompassing the entire museum-building process from spatial layout to guided navigation, are scarce. Integrated tools, such as ArkaeVision, begin to address this by offering interactive, user-centered explorations of specific sites, combining virtual reconstructions and storytelling [30].

Despite these advancements, several challenges in interior design hinder effective heritage preservation. Issues such as lack of standardization in space conditioning, insufficient staff training, and inadequate resources can undermine digitization efforts [31].

Additionally, poor configurations between interior design and the museum's functional needs can compromise both functionality and visitor experience [32]. The absence of a comprehensive approach to assessing factors affecting visitor experience can result in ineffective management, limiting the scope of strategies aimed at improving public satisfaction and engagement [33]. Consequently, the integration of virtual and physical exhibitions, along with a lack of strategic planning to meet contemporary digital demands, restricts museums' abilities to attract and retain visitors in an evolving digital landscape [34]. However, such systems often cater to limited applications and lack broad adaptability. Comprehensive solutions that unify all aspects of virtual museum design, including room construction, artifact placement, and route recommendations, could help bridge this gap. Such an approach would enable museums to deliver cohesive, immersive experiences that fully engage visitors throughout their journey.

1.3. Virtual Museum of Maule

This case study describes the virtual museum of Maule in Chile [9]. The virtual museum of Maule features four distinct collections: (1) Pre-Columbian Cultures; (2) Colony, Crafts, and Rural Life; (3) Chilean Independence; and (4) Pedro Olmos. Each collection consists of 3D pieces organized by the time period they represent. These pieces were created through a digitization process utilizing photogrammetry and 3D scanning techniques [35] . The collection of Pedro Olmos was digitized through high-definition photography, as the paintings are 2D objects. In the virtual experience, once the user chooses a collection, they can walk freely in the virtual environment. The user can select one piece with the keyboard and mouse and interact with them. The software shows users an interface where they can appreciate the 3D object in 360 degrees, access information, such as which museum the piece is from, and learn cultural and general information.

Despite the promising progress that the virtual museum of Maule has made in the dissemination of its digital heritage collection, the design of the experience has limitations that constrain the user experience. For instance, generating new 3D environments and accurately positioning artifacts within the virtual space are highly time-consuming tasks, for both designers and developers. Additionally, the artifact layout often follows a linear or sequential format as illustrated in Figures 1 and 2, leading to repetitive experiences, as each room presents artworks in a uniform, isolated manner, which in this case is part of the presentation and experience curation. Museum layouts frequently remain fixed, even when physical dimensions allow for variability. This uniformity can dilute each room's distinct identity. Addressing these issues requires a system that not only optimizes artifact arrangement but also dynamically plans visitor routes to enhance both interactivity and spatial flow.

1.4. Motivation

Taking into consideration the previous sections, there is an opportunity to enrich the design and development process with a mixed-initiative tool, giving the designer or developer automated options to create new environments for developing virtual museums. This will reduce the development time and contribute to the creation process without losing control of the main design of the virtual experience. These tools contribute positively to the creation process [36,37].

Figure 1. A standard arrangement of artwork inside the museum; example from the room of Pre-Columbian Cultures of the virtual museum of Maule.

Some strategies that could improve the layout generation, in this context, come from other engineering problems such as (1) the Online Bin Packing problem, a combinatorial challenge aimed at efficiently placing items of varying sizes into fixed spaces [38–42]; and (2) Guillotine Cutting, in which spaces are optimized by making precise rectangular cuts from a larger area, although it often prioritizes space efficiency over layout diversity [43–45].

In this sense, to enhance diversity in digital environments, Genetic Algorithms (GAs) have shown success in generating layouts that maximize space utilization while introducing variety, crucial for virtual museums [46–48].

Binary Space Partitioning (BSP) subdivides spaces using hyperplanes, streamlining the creation of indoor environments [49–51]. The artwork placement requires balancing layout diversity with efficient positioning strategies. While Genetic Algorithms are effective for this stage, they are not the only approach; other mono-objective techniques, such as Greedy algorithms and Particle Swarm Optimization (PSO), can also be considered. Greedy algorithms prioritize immediate optimizations, arranging artworks based on local maximization criteria but potentially neglecting overall distribution harmony. PSO, in contrast, is effective in clustering artworks dynamically by simulating "swarm" behavior, though it may converge prematurely without introducing sufficient layout variability [52]. Comparatively, GAs offer a balance between efficient placement and layout diversity due to their iterative and population-based approach, which allows for gradual refinement and adaptability in museum settings [53].

The novelty of the proposed system lies in its integration of Binary Space Partitioning for efficient layout generation and Genetic Algorithms for optimizing artwork arrangement within a unified framework. While previous approaches have explored Procedural Content Generation for virtual environments [54,55] and optimization methods for space planning [56,57], this work is the first, to the authors' knowledge, that combines these techniques for the specific case of virtual museum design. By leveraging BSP for rapidly generating diverse floorplans and GAs for intelligently arranging exhibits, the system enables the efficient creation of engaging, navigable museums that are spatially expressive and content-rich. This addresses key challenges in virtual museum development, allowing designers to focus on curation and aesthetics while ensuring a coherent, immersive visitor experience.

Figure 2. Examples of artwork hanging on the museum walls, example from the room of Pedro Olmos of the virtual museum of Maule.

The contribution of this article lies in a two-phase integrative system designed to contribute to the development process of a virtual museum in the generation of digital environments. This system consists of (1) a Room Generator, which tackles the challenge of creating varied and dynamic spatial configurations to enhance user engagement. The Room Generator stage benefits from multi-strategy models like GAs and BSP, providing spatial efficiency with adaptability, which is essential for a flexible digital environment; and (2) an Artwork Arrangement stage, which optimizes artwork placement using Genetic Algorithms to maximize space utilization and aesthetic diversity, addressing the challenge of efficient content arrangement while providing flexibility and adaptability in placing diverse artwork collections within varied virtual environments.

This paper is organized as follows: Section 2 presents the Design and Creation methodology, detailing its five steps and their application in the research process, including the materials and methods used in developing the virtual museum generator. Section 3 outlines the findings, highlighting the software's outputs and results. Section 4 discusses these findings, offering recommendations based on the development experience and evaluating each step of the design and creation strategy. Finally, Section 5 presents the conclusions and future directions for research in this domain.

2. Materials and Methods

This research follows the *Design and Creation* methodology [58], an iterative five-step approach, integrating research and development. The methodology comprises five steps: (1) Awareness: Identification of a problem or opportunity through literature review and contextual observation; (2) Suggestion: Suggesting a solution framed by a conceptual design; (3) Development: Designing and implementing an initial prototype; (4) Evaluation: Evaluating results from the experimental phase; and (5) Conclusion: Drawing conclusions from the research. Steps 1, 2, and 3 are detailed in this section, while Steps 4 and 5 are addressed separately in their own sections. This methodology provides guidelines for developing a museum generator that enhances the design of virtual environments. The experience is built using the Unity 3D framework version 2022.3.52f1 and C# programming language, with data stored locally and analyzed using Python 3.11.3.

2.1. Awareness and Suggestion

The proposed virtual museum generator addresses the previously identified challenges in two sequential stages, each tailored to optimize user experience through dynamic room layouts, optimized artwork arrangements, and intelligent route planning. The system's performance is assessed in two distinct phases to ensure the effectiveness of each stage in meeting the design goals. Figure 3 illustrates the steps involved in each stage and the interaction between the developer and the system, highlighting the developer's role in the human-in-the-loop process. A detailed description of each stage and its corresponding steps is provided below.

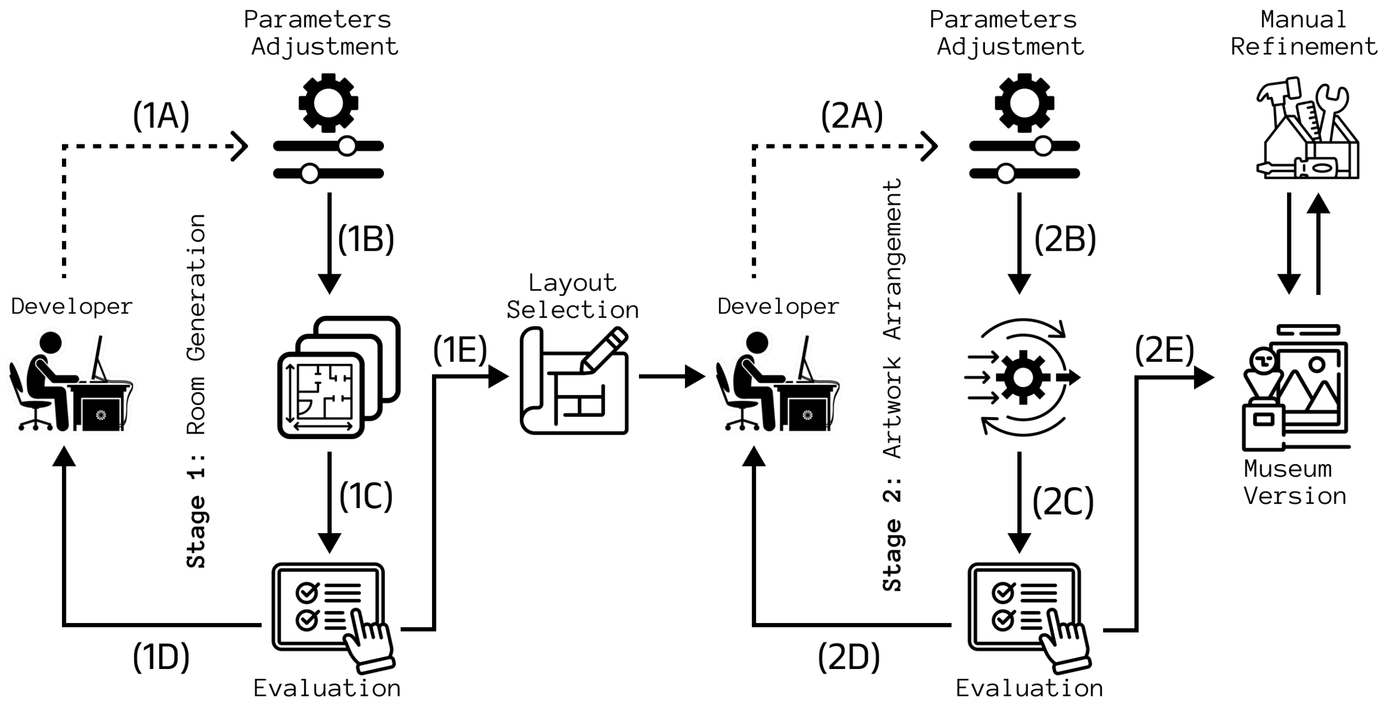

Figure 3. Human-in-the-loop interaction in the virtual museum generation process. Stage 1 (Room Generator) consists of five iterative steps: parameter adjustment (1A), room generation (1B), evaluation (1C), refinement if necessary (1D), and selection of the optimal layout (1E). Stage 2 (Artwork Arrangement) follows a similar process: parameter adjustment (2A), artwork distribution generation (2B), evaluation (2C), refinement if necessary (2D), and selection of the final distribution (2E). After both stages, manual refinements can be performed to further optimize the virtual museum.

- Stage 1 (Room Generator): In the first stage, the BSP method will be used to generate rooms of various sizes and positions within the virtual museum. The goal is to create multiple room configurations that offer greater flexibility in spatial design. This approach aims to reduce the monotony of traditional layouts and enrich the visitor experience through dynamic spatial arrangements. This stage follows a human-in-the-loop process consisting of five steps: (1A) the developer adjusts the parameters of the room generation module, (1B) the system generates multiple room configurations, (1C) the developer evaluates the generated layouts, (1D) if unsatisfactory, the parameters are readjusted for a new iteration, and (1E) the most suitable layout is selected for the next stage. To evaluate the performance of this stage along with Stage 2, a grid-based assessment will be conducted to identify the optimal operator configurations for the room generation task.

- Stage 2 (Artwork Arrangement): This stage utilizes GAs within the Artwork Arrangement module to optimize the placement of artworks within the generated rooms. Given a museum layout and a set of artworks, the GAs will maximize space utilization and provide visually appealing, diverse configurations. The GA operator settings will be adjusted to balance generation speed with deep exploration of the solution space. Stage 2 follows a similar human-in-the-loop approach, consisting of five steps: (2A) the user adjusts system parameters for artwork distribution, (2B) the system generates a distribution of artworks, (2C) the user evaluates the generated distribution, (2D) if unsatisfactory, the parameters are readjusted for a new iteration, and (2E) the final distribution is selected. After this stage, manual refinements can be performed by developers or curators to fine-tune the final virtual museum. This adjustment will be evaluated together with Stage 1 through grid-based assessments to determine the optimal combination of operators.

2.2. Development

The Room Generator, which forms Stage 1 of creating the virtual museum environment, defines the spatial layout based on user-provided dimensions. Users specify the width, height, and maximum room size, allowing the system to subdivide the area into distinct rooms. This layout generation employs an adaptable Binary Space Partitioning (BSP) algorithm [59] that produces a variety of configurations, differing in room size, quantity, and spatial arrangement, from which the user can select a preferred design (see Figure 4).

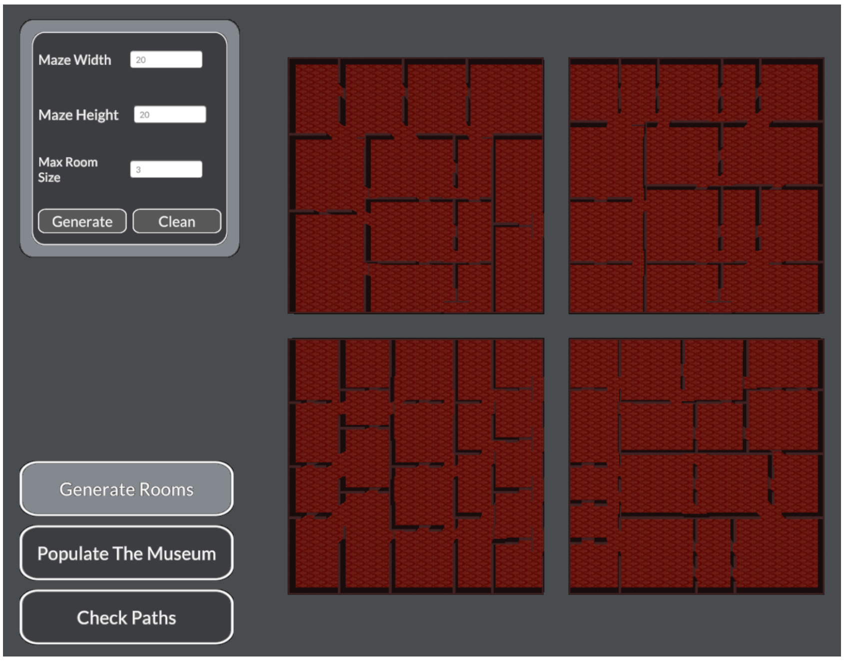

Figure 4. Different room layouts generated from the Binary Space Partitioning algorithm. The system requests the width and height of the museum in meters, as well as the maximum size of the rooms.

To support flexibility in layout adjustments and future modifications, the system translates each configuration into a simplified, structured model, where each segment of the virtual space is assigned a basic structure type (e.g., wall, floor, or door). This abstraction helps map out areas for different functionalities within the museum, such as accessible paths and exhibit placement. Visual representations are then created to help users intuitively assess each layout option and identify spaces designated for art displays (see Figure 5).

These options allow the user to control the environment's setup and design, which is a key feature of mixed-initiative systems [60]. The technology helps and supports the process by providing users with options and reducing time-consuming activities. In the context of virtual museums, having control over the design is particularly significant since collections and pieces are part of a central narrative and curation process that is key for the virtual product [61].

0	0	1	1	1	1	1	1	1	0	0
0	0	1	2	2	2	2	2	1	0	0
1	1	1	2	2	2	2	2	1	1	1
1	2	2	2	2	2	2	2	2	2	1
1	1	3	1	1	1	1	1	1	3	1
1	1	3	1	1	1	1	1	1	3	1
1	2	2	2	1	1	2	2	2	2	1
1	2	2	2	3	3	2	2	2	2	1
1	2	2	2	3	3	2	2	2	2	1
1	1	2	2	1	1	2	2	2	1	1
0	1	3	3	1	1	3	3	1	1	0

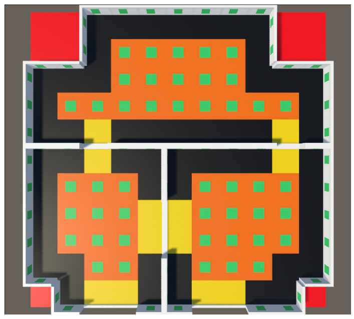

Figure 5. Museum representation. The left figure shows the numerical representation of the virtual museum, where values correspond to structures in the environment: 0 represents non-traversable areas, 1 represents walls, 2 represents floors, and 3 represents doors. The right figure shows the visual representation of the virtual museum, using different colors to identify each structure in the space (0 is represented as red, 1 as gray, 2 as orange with green points in the center, and 3 as yellow).

2.3. Artwork Arrangement

This stage focuses on arranging the artwork placement within the generated museum layout, optimizing distribution to ensure both accessibility and aesthetic balance. The implementation utilizes a Genetic Algorithm, which iteratively refines the artwork placement by evaluating multiple layout configurations and selecting the most effective arrangement based on predefined criteria. Each potential layout configuration translates into a simplified, one-dimensional mapping of floor spaces, converting the spatial organization into a manageable form. The process retains only feasible configurations that meet the spatial and accessibility requirements. Figure 6 illustrates the overall approach to transforming the layout for the artwork placement.

0	1	1	1	0
1	1	2	2	1
1	2	2	2	1
1	2	2	2	1
1	3	1	3	0

0	0	0	0	0
0	0	1	1	0
0	1	1	1	0
0	1	1	1	0
0	0	0	0	0

Sea a = 0 0 0 0 0
Sea b = 0 0 1 1 0
Sea c = 0 1 1 1 0
Sea d = 0 1 1 1 0
Sea e = 0 0 0 0 0

a	b	c	d	e

Sea g1 = [0,8,0]
Sea gn = [0,19,0]

g1	...	gn

Figure 6. Genetic Algorithm steps to extract the representation of the museum space from a 2D matrix. Starting with a matrix of a generated room, a binary matrix is created to store the floor positions. A one-dimensional mapping then records the floor values row by row. Finally, these data are used to construct a chromosome vector, where each gene encodes whether a position contains a piece, its relative position, and a legality marker for offspring validation.

To enhance user control in this process, the system allows for the customization of the Genetic Algorithm by providing various configuration options, such as population size, number of generations, and the inclusion or exclusion of elitism. Additionally, users can adjust the selection strategy (rank, roulette, or tournament), crossover method (single point, two point, or uniform), and mutation technique (inversion, random resetting, scramble, or swap) to explore different possibilities in the artwork arrangement.

Providing users with control over these parameters enhances the adaptability of the system, allowing it to respond to different curatorial needs and exhibition styles. Rather than generating a single automated solution, the approach encourages an interactive refinement process where curators can explore multiple possibilities before selecting the most suitable configuration. This increases the likelihood that the computational arrangement aligns with both the efficiency requirements and the artistic and narrative intentions of the exhibition.

3. Results

The system was implemented in Unity Engine version 2022.3.52f1 using C# as the programming language; it is available at a GitHub repository [62].

Experiments were conducted to evaluate the performance of different combinations of genetic operators for the artwork arrangement task in the virtual museum generator. The experiments were run on a notebook manufactured by Asus model TUF Gaming F15 with an Intel® Core™i5-10300H CPU @ 2.50 GHz and 16 GB of RAM.

3.1. Experimental Setup

A total of 36 combinations of genetic operators were evaluated using a grid search approach, focusing on variations in the selection, crossover, and mutation operators. Each combination was tested in 10 independent runs, and the results were averaged. The evaluation metrics were (a) the average best fitness, representing the proportion of floor space occupied by artworks, and (b) the average time required to find the solution with the highest fitness. The hyperparameters used were population size (10), number of evaluations (100), elitism size (2), tournament size (5), mutation chance (0.01), and crossover chance (0.9). A detailed comparison of the average performance of each combination of operators is presented in Figures A1–A4 in the Appendix A.

3.2. Fitness Analysis

Four distinct operator combinations achieved the highest average best fitness of 45.55 as shown in Table 1 (gray rows). Given that the remaining space is reserved for navigation, this result indicates a highly effective solution. Combinations employing roulette selection performed worse on average, with the lowest fitness of 30.1 obtained by the configuration "TwoPoint, Random Resetting, Roulette".

3.3. Computational Time Analysis

Configurations with ranking selection tended to produce more infeasible solutions but converged faster to optimal solutions. In contrast, roulette selection configurations balanced the solution discovery time with handling invalid chromosomes, effectively navigating the solution space. Tournament selection was the least time efficient for finding optimal solutions.

3.4. Comparative Analysis of Top Combinations

A comparative analysis of the four combinations with the highest average fitness revealed that ranking and tournament selection were the most suitable for efficient exploration of the search space. Ranking selection exploited the search space effectively, converging quickly to optimal solutions, while tournament selection provided better exploration at the cost of slower convergence. Both uniform and two-point crossover were effective strategies for exploration, with uniform crossover performing slightly better, although the difference was not statistically significant. All optimal combinations utilized swap mutation, indicating its suitability for this problem.

Table 1. Performance of genetic operators in different configurations.

Crossover	Mutation	Selection	Valid Chromosomes	Invalid Chromosomes	Time (ms)	Best Fitness
SinglePoint	Inversion	Rank	110.90	899.10	115.70	44.16
		Roulette	812.90	197.10	354.00	39.31
		Tournament	849.50	160.50	499.60	44.06
	RandomResetting	Rank	79.70	930.30	109.20	36.34
		Roulette	740.90	268.10	296.20	31.39
		Tournament	725.50	284.50	431.70	38.71
	Scramble	Rank	109.10	900.90	130.80	44.06
		Roulette	825.20	184.80	369.60	38.71
		Tournament	851.40	158.60	503.30	43.96
	Swap	Rank	97.30	912.70	105.90	44.26
		Roulette	804.30	205.70	300.00	32.08
		Tournament	812.40	197.60	484.60	44.26
TwoPoint	Inversion	Rank	293.20	716.80	89.50	43.76
		Roulette	843.10	166.90	336.80	38.32
		Tournament	893.00	117.00	487.30	43.76
	RandomResetting	Rank	75.90	934.10	90.70	36.04
		Roulette	750.60	259.40	300.30	32.08
		Tournament	722.90	287.10	428.80	38.12
	Scramble	Rank	285.80	724.20	102.00	44.16
		Roulette	840.60	169.40	363.30	39.50
		Tournament	863.30	146.70	504.00	44.16
	Swap	Rank	92.80	917.20	113.50	**44.55**
		Roulette	799.80	210.20	335.70	34.65
		Tournament	832.50	177.50	526.10	**44.55**
Uniform	Inversion	Rank	146.30	863.70	120.40	44.16
		Roulette	792.00	218.00	389.00	43.07
		Tournament	863.80	146.20	515.80	44.16
	RandomResetting	Rank	73.40	936.60	78.50	35.15
		Roulette	712.20	297.80	285.30	30.50
		Tournament	688.60	321.40	417.60	37.03
	Scramble	Rank	150.20	859.80	128.40	44.26
		Roulette	808.60	201.40	349.50	40.20
		Tournament	854.30	155.70	506.00	44.26
	Swap	Rank	128.20	881.80	109.00	**44.55**
		Roulette	795.70	214.30	354.90	39.31
		Tournament	835.80	174.20	522.00	**44.55**

Rows highlighted in gray indicate configurations that achieved optimal results. The value in the "Best Fitness" column is calculated using the formula: (x = 1 − (fitness obtained by the algorithm)). This conversion was made to better illustrate the percentage of museums with artworks placed.

3.5. Path Verification Module

A path verification module was developed to ensure the feasibility of the generated museum layouts that recognize paths inside the virtual museum. This module makes an algorithm verification of the proposed layout. The verification checks if the layout is walkable from beginning to end. Given an initial configuration, the system constructs a representation of the space capturing the connections between rooms and their key access points. Using the Held–Karp heuristic [59], optimal internal paths were calculated, considering the positioning of exhibits and entry points. The verification process involved four sub-stages as illustrated in Figure 7: (A) identifying room structure and navigable areas; (B) configuring artwork placement; (C) assigning unique codes to rooms; and (D) combining these configurations to verify that the space is traversable.

This module was developed to check if the solution proposed by the system could effectively allow travel through the virtual world from each proposed point. Nevertheless, the developers or designers can freely modify the arrangement of the elements within the virtual world in order to be able to provide the desired experience for end users. The principal objective of this mixed-initiative tool is to provide an input so that it can be reused by the curator team to generate a better experience, minimizing the time and resources used in the development process.

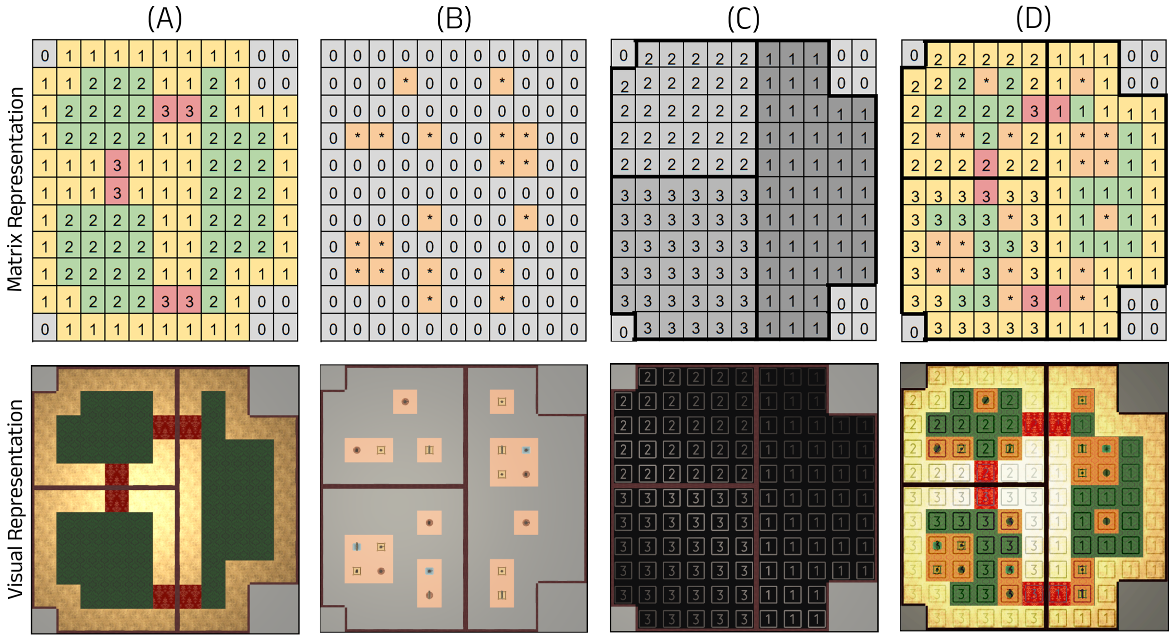

Figure 7. Path verification inside the virtual museum. (Step (**A**)) represents the structure of rooms in the virtual museum (0 → non-navigable space; 1 → walls; 2 → floors; 3 → doors), based on the information from Stage 1. (Step (**B**)) represents a valid configuration of pieces within the museum, derived from Stage 2. (Step (**C**)) identifies each room with a unique code based on the distribution from Step (**A**). (Step (**D**)) combines Steps (**A**–**C**), integrating the information layers from Stages 1 and 2 to verify connectivity within the museum.

4. Discussion

Based on the observations from stages 1 and 2, combining BSP for museum layout generation and GA for artwork arrangement could significantly enhance museum design efficiency and reduce development time. Although various combinations of operators yield suitable museum layouts, the speed and effectiveness of the solution depend heavily on the selected operator configuration.

Using the setup of the virtual museum of the Maule case, the analysis shows that ranking selection yields faster solutions (78.5–130.8 ms; see Table 1) than other methods, though it produces more invalid chromosomes. In contrast, tournament selection explores the solution space more comprehensively, although it is slower. Experiment 1 presents certain limitations that may affect the evaluation of the data. Firstly, the experiment only considers floor-piece placement to determine fitness, leading to multiple solutions with similar fitness values that do not necessarily improve user engagement over a sequential layout. This constraint limits the capacity to assess whether layout variations impact users' perception of a traditional museum. Secondly, the fitness evaluation does not incorporate wall-piece placement, restricting the ability to evaluate how these elements influence the feasibility and appeal of a given layout.

On the algorithmic front, both stages could be improved by implementing alternative techniques and comparing their performance to the current ones. Alternatives for the Room Generator range from classic algorithms, such as agent-based or grammar-based, [63] to newer methods, like wave function collapse (WFC) [64] or machine learning-based generators [65]. The Artwork Arrangement stage seems well suited for optimization or search-based techniques [66] as shown by the GA in this article. Other search-based techniques, such as simulated annealing or Particle Swarm Optimization should be implemented and their performance assessed.

Finally, from a development perspective, the proposed system shows promise in generating structured and diverse virtual museum environments as illustrated in Figure 8. The combination of BSP and GA facilitates the exploration of different spatial configurations while maintaining a logical organization of exhibition spaces. While the generated layouts appear to support a variety of exhibition styles, further evaluation with museum visitors would be needed to assess their impact on navigability and user experience. Additionally, incorporating more refined constraints, such as visitor flow analysis or thematic grouping, could enhance the system's adaptability, potentially making it a valuable tool for curators and designers seeking to experiment with different layout configurations.

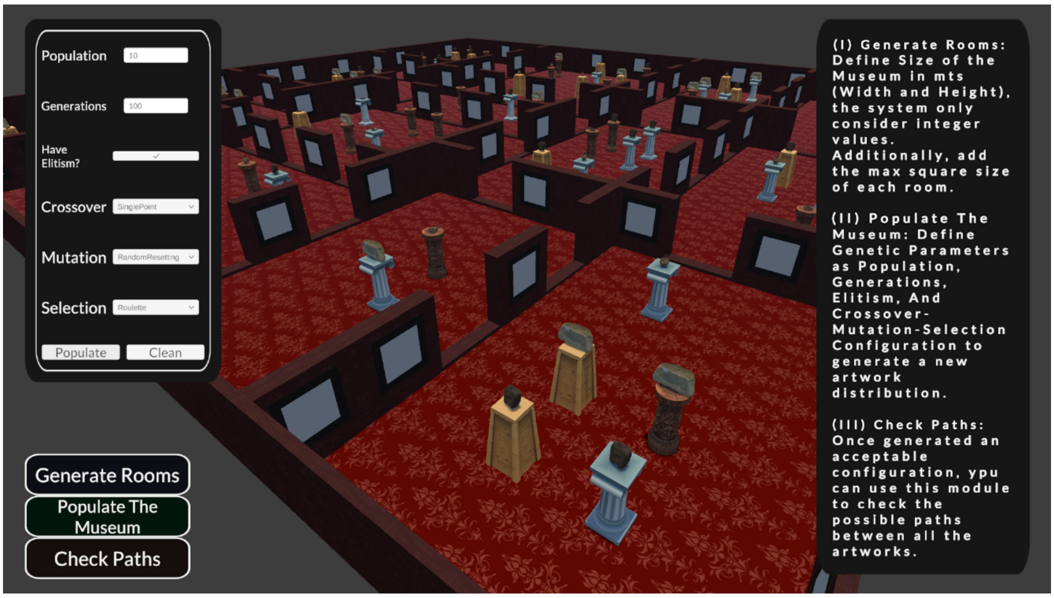

Figure 8. Example from the Unity inspector with a final representation of the generated scene for the virtual museum using the proposed system.

5. Conclusions and Future Work

This study presents a framework for generating diverse virtual museums, addressing the need for designers to create interactive environments. A two-stage virtual museum generator was developed and made available at [62]. The first stage generates diverse room layouts, while the second arranges artwork using Genetic Algorithms (GAs).

An experiment was conducted taking the virtual museum of Maule as an input experience. The experiment focuses on stages 1 and 2. Here, a grid combinatorial analysis of 36 combinations of genetic operators was conducted. The findings revealed that only four configurations achieved optimal performance in terms of fitness: (a) (Uniform, Swap, Rank); (b) (TwoPoint, Swap, Rank); (c) (Uniform, Swap, Tournament); and (d) (TwoPoint, Swap, Tournament). These results suggest that selection methods significantly influence the algorithm's average time to reach optimal configurations. Configurations that yield a higher number of infeasible solutions correlate with faster average times, suggesting an emphasis on exploration, while those producing fewer infeasible candidates require more time but explore the solution space more thoroughly. Notably, even the least effective operator combination generates spaces of 121^2 m in under 3 s, with the best configurations achieving this in under 550 ms as shown in Table 1. A concern could be that the generation of a fixed exhibition space structure, rather than a dynamic experience that changes based on visitor's interactions with the pieces, could limit the visitor experience and educational opportunities. However, it is important to note that this tool is designed to enhance the curator and designers' ability to define rooms, elements, and pieces according to a central narrative or a specific thematic focus. There is indeed a fundamental design decision to make regarding the balance between predetermined exhibition spaces and more open-ended, exploratory environments. This tool, when generating a virtual museum, though it generates a space with predefined rooms, aims to offer the visitors a free-flowing experience in the sense that, rather than a pre-recorded video or rooms with only one door that force visitors to walk a single path, allows visitors to experience pieces in their own time and order, with multiple doors and routes, according to the decisions of the museum team.

A key advantage of the proposed approach is its adaptability, enabling recommendations applicable in real-world contexts. This spatial interpretation capability extends beyond virtual museums, with potential applications in diverse development stages , such as architectural design and real museum environments. That is, the modeled concept can be of great potential in an exhibition design of real, non-virtual museum exhibitions where the space is predefined. For example, in temporary exhibitions or in redesigns of permanent spaces, museum teams can create models to implement in real, physical spaces.The system's design further optimizes the time required to generate feasible recommendations, crucial for creating engaging user experiences in a wide range of interactive applications. However, the models created in the virtual space may need modifications to meet the needs of physical spaces, such as wall placement, etc.

This implementation holds strong implications for Human–Computer Interaction (HCI), as it enhances the relationship between designers or developers and digital systems by allowing for the quick generation of personalized, high-quality virtual spaces. The ability to rapidly create diverse and navigable environments can empower software users to explore, interact, and customize their digital experiences, fostering a more seamless and immersive user experience.

Moreover, this framework offers significant benefits to virtual space developers and museum designers by facilitating the creation of dynamic environments for their projects. By providing tools for quickly generating varied layouts and optimized navigation paths, the proposed approach allows designers to focus on creativity while ensuring a high-quality user experience.

The adaptability of this implementation for real-world applications broadens its potential uses in route planning across various settings. Future work should prioritize evaluating user experience and customizing the system for various environments, including the possible application of the system to real-world exhibition design, and devices to maximize its effectiveness and acceptance.

Additionally, this framework can serve as a valuable tool for empowering designers and developers to rapidly create personalized, interactive virtual environments that cater to diverse user preferences and needs. The ability to quickly generate a wide range of navigable spaces can foster a more engaging and immersive user experience, ultimately enhancing the relationship between digital systems and their users. Future research should also explore ways to further optimize the algorithm's performance and integrate more advanced personalization features to better accommodate user-specific requirements across a variety of applications, from virtual museums to architectural design and beyond.

Future Work

While the system can verify that space is walkable (with the Path Verification Module), it is not possible to know a priori if the proposed version of the virtual museum is more engaging for real users.

Therefore, a usability study would be beneficial to gauge user satisfaction, specifically regarding how well the system meets their needs. Such a study would allow for an understanding of how the system could be enhanced by enabling users to prioritize certain rooms or exhibits, or by generating recommendations based on personal preferences. This user-testing, along with curator feedback, would allow the technical functionality to have a greater impact on visitor experience.

Future work should focus on optimizing the algorithm and testing its performance outside of controlled lab environments. Additionally, a comparative study between a control condition (traditional museum layout) and the optimized layout proposed in this research could be carried out to evaluate if the proposed design is more appealing. Implementing more personalized recommendations would further enhance the system, allowing users to prioritize museum areas based on their preferences.

Regarding usability, visitor engagement, and interdisciplinary collaboration, in light of the tool's goal of supporting the creation of meaningful and engaging virtual museum experiences, the potential impact of this design model is that visitors' will have the opportunity to interact with the curators' and designers' vision for the museum.

From a technical point of view, new functionalities could be implemented, such as adding unique tags to a specific group of 3D pieces that are part of a collection. This would improve the system's distribution of collections and give users more control over the distribution of certain rooms.

Finally, the proposed tool allows designers and developers to create different layouts with the position of pieces based on an algorithmic generation, which results in saving resources, like time, and supports the creation and thought process without losing control of it; it is expected to contribute to the development process in an interdisciplinary team. We aim to keep working on including new features and rules to the algorithms that allow us to include narratives, themes, and unique characteristics of the pieces to enable museum curators, museographers, or users without technical knowledge to create virtual museums by not only creating layouts and positioning pieces but also complementing this with special features and narratives.

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Abbreviations

The following abbreviations are used in this manuscript:

PSO	Particle Swarm Optimization
GA	Genetic Algorithm
BSP	Binary Space Partitioning
WFC	Wave Function Collapse
HCI	Human–Computer Interaction

Appendix A. Analysis of System Performance

Appendix A.1. Time Performance

Figure A1. Grid analysis of average time performance for 36 operator combinations in 10 independent experiments. The combination of "Uniform, RandomResetting, and Rank" achieves the fastest execution time at 78.5 ms, while the combination of "TwoPoint, Swap, and Tournament" results in the slowest time at 526.1 ms.

Appendix A.2. Fitness Performance

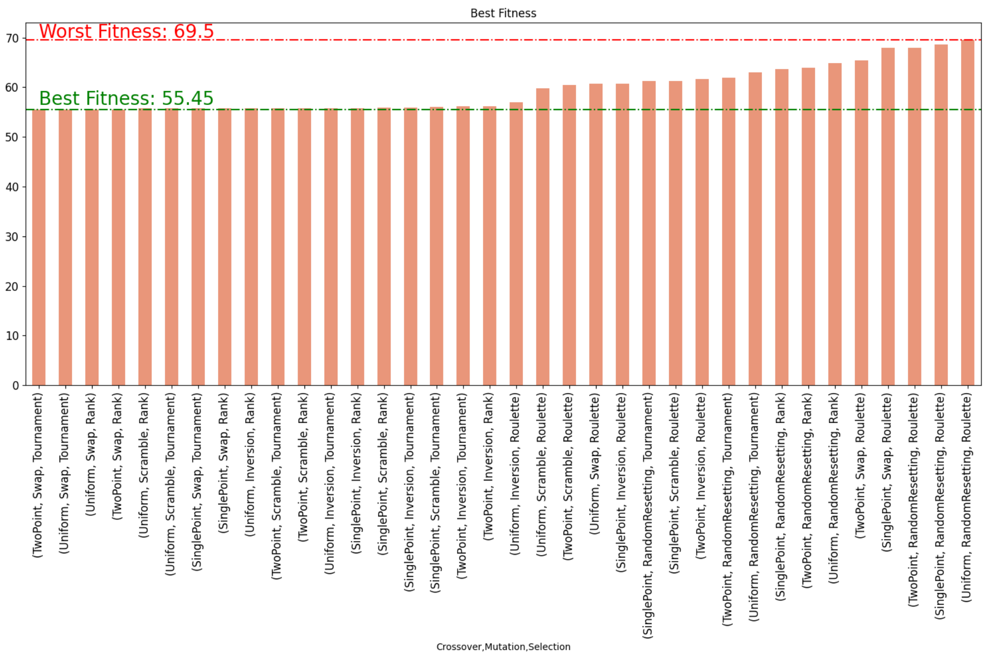

Figure A2. Grid analysis of average time performance across 10 independent experiments for 36 operator combinations. The combination of "TwoPoint, Swap, and Tournament" achieves the best fitness with 55.45% free space, meaning 44.55% of the space is occupied by artworks. In contrast, the combination of "Uniform, RandomResetting, and Roulette" results in the lowest fitness, with 69.5% free space, indicating only 30.5% space occupancy and lower efficiency compared to other approaches.

Appendix A.3. Valid Choromosomes Performance

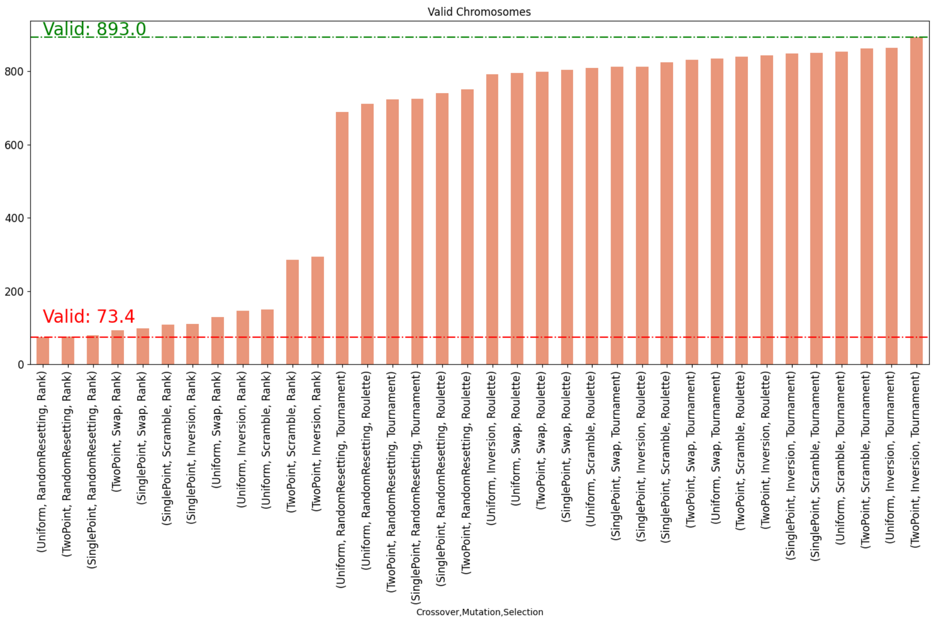

Figure A3. Grid analysis of the average number of valid chromosomes across 10 independent experiments for 36 operator combinations. Each experiment involves a total of 101 chromosomes, meaning each combinatorial approach analyzes 1010 chromosomes. The combination of "TwoPoint, Inversion, and Tournament" achieves the highest average number of valid chromosomes, with a value of 893.0. In contrast, the combination of "Uniform, RandomResetting, and Roulette" results in the lowest number of valid chromosomes, with an average of 73.4. The primary reason for these differences is the genetic pressure exerted by the selection operator during evaluations.

Appendix A.4. Time and Valid Chromosomes Comparison for Operators with Best Average Fitness

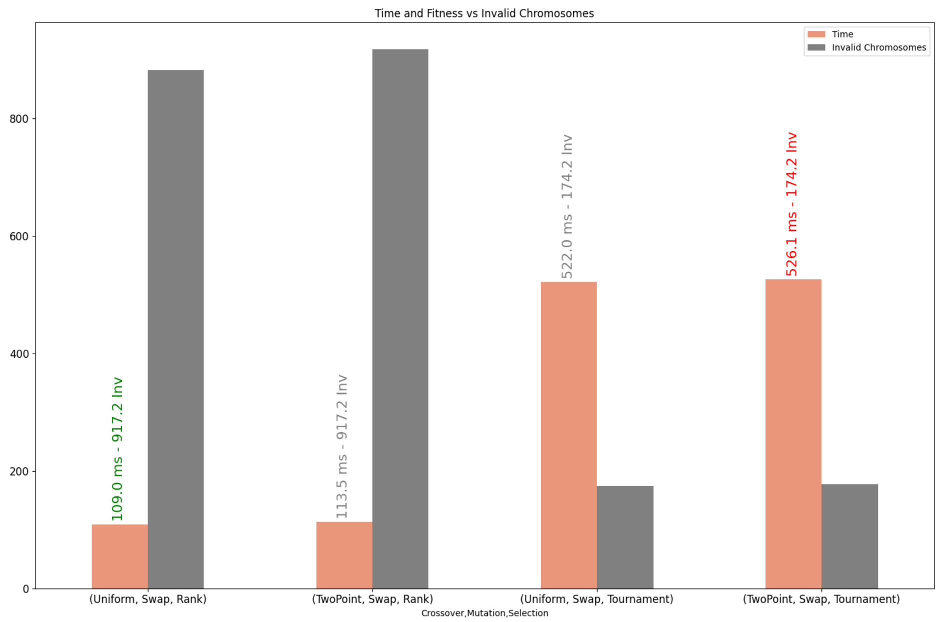

Figure A4. Grid analysis of the average number of valid chromosomes across 10 independent experiments for 36 operator combinations. A comparative analysis of the top four combinations with the highest average fitness shows that ranking and tournament selection are most effective for search space exploration. Ranking selection converges quickly to optimal solutions, while tournament selection offers better exploration but slower convergence. Both uniform and two-point crossover are effective, with uniform crossover performing slightly better, though the difference is not statistically significant. All optimal combinations use swap mutation, highlighting its suitability for this problem.

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