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TOWARDS A FINER HERITAGE MANAGEMENT

Evaluating the Tourism Carrying Capacity using an Agent-Based Model

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Abstract. As one of the most important areas in the Palace Museum, Beijing, China, the Hall of Mental Cultivation had suffered from overcrowding of visitors before it was closed in 2016 for conservation. Preparing for the reopening in 2020, the Palace Museum decided to take the chance and initiate finer-grained tourism management in the Hall. This research intends to provide an audio-guided touring program by dynamically evaluating the Tourism Carrying Capacity (TCC) with the highlight spots in the Hall, to operate the touring program spatiotemporally. Framing an optimization problem for the touring program, an agent-based simulator, Thunderhead Pathfinder, originally developed for evacuation in the emergency, is utilized to verify the performance of the touring system. The simulation shows that the proposed touring program could precisely fit all the key requirements to improve the visitors' experience, to guarantee heritage safety, and to ensure more efficient management.

Keywords. Tourism Carrying Capacity; Agent-Based Simulation; Operations Research; Heritage Management.

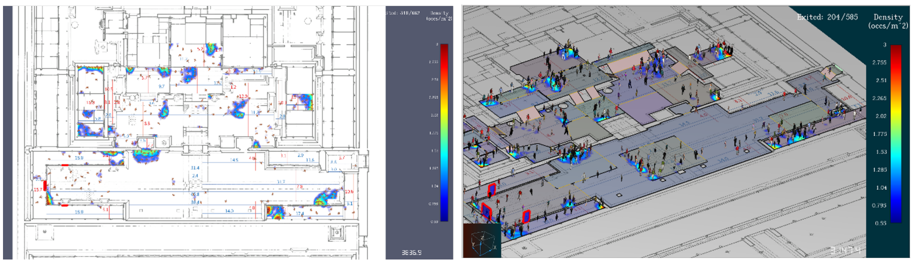

Figure 1. The simulation result as screenshots in Pathfinder software. Left: An instant density graph of the agents in the Hall; Right: The distribution of agents' movement in 3D.

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1. BACKGROUND

Constructed in the early 17th Century, the Palace Museum (or The Forbidden City) in Beijing witnessed the rise and fall of Ming and Qing Dynasties. The palace was established as a museum in 1925, and was inscribed on the UNESCO world heritage list since 1987. Being one of the most important areas in the Palace Museum, Hall of Mental Cultivation (or Yangxin Palace) has served as the residential and working place for eight emperors in Qing Dynasty for more than 300 years (See *Figure 2d and 2e*). A major research project was initiated in 2016 on the Hall, intended to fully research on, conserve, restore, and further monitor the heritage site scientifically. Having been closed for conservation for 5 years, the Hall is planned to reopen in 2020 with special temporary and permanent exhibitions demonstrating the outcome of research and restoration, intended to celebrate the 600th anniversary of this grandiose heritage.

Before the conservation project started, the Hall of Mental Cultivation could have been visited by any visitor at any time, which led to a sensational overload of the area all over the year. As is shown in *Figure 2*, for 80% days of the year 2014-2015, visitors entering the Hall, the accessible area of which is only 1,000 m2, could reach 7,200 to 19,000 people per day, with 800 people staying in the Hall spontaneously. The Palace Museum has decided to set the daily reservation limit of visitors to 80,000 in June 2015, to improve the visitors' experience, to guarantee the safety of the heritage and to ensure more efficient management. Even after the limitation, the Hall of Mental Cultivation still could suffer from being visited by more than 20,000 people per day. Due to the overcrowding, the weakening of the heritage had been rather severe, urging for the conservation project (Zhang, Zhang, and Chen 2015).

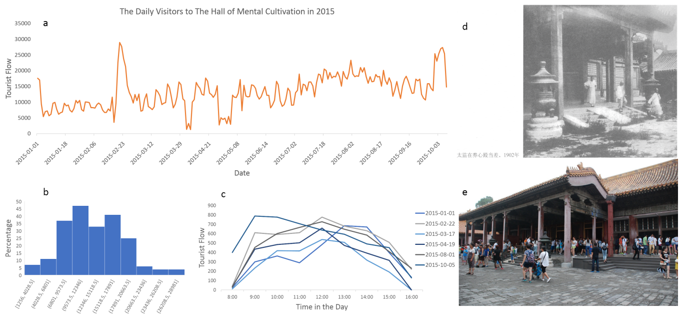


Figure 2. a) The number of daily visitors to the Hall of Mental Cultivation in 2015; b) the histogram showing the distribution of the daily visitors to the Hall in 2015; c) the instant visitors in the Hall for different time of the day in several typical days in 2015; d) the Hall in 1902; e) the Hall in 2015. SOURCE: a) to c) drawn by authors with the data of Department of Architectural Heritage, the Palace Museum; d) Lin J (2016), Hundred Year Photograph in Ancient Beijing. The Forbidden City Press; e) photo taken by Di Y from the Palace Museum.

Taking this chance of reopening the Hall after conservation, the Palace Museum intended to initiate an even finer-grained level of heritage management, which could respond to the instant tourism condition and recommend optimal alternatives, both to the visitors and to the operators (Shan 2018). As a starting point, this research intended to provide an outline for the new touring program in the Hall of Mental Cultivation, which could balance the tourist flow spatiotemporally. Under such a condition, the traditional way to calculate the Tourism Carrying Capacity (TCC) statically has been updated with the aid of computer programming and agent-based simulation, in order to better fit and adjust the instant tourist dynamic.

2. CONTEXT

2.1. TOURISM CARRYING CAPACITY

Tourism Carrying Capacity (TCC) can be defined as "the maximum number of tourists that can be contained in a certain destination area", considering both the issues of the negative impact of tourism on the site and the quality of the experience of tourists themselves (O'Reilly, 1986). This concept has been broadly applied in tourism site management around the world, by measuring the number of tourists in an area, usually compared as to the extent of the area occupied per person. However, some scholars such as (Mc Cool & Lime, 2001), argue that the numeric pursuit of TCC may rarely reflect the real issue, and that we should reformulate the question from being about a quantitative spatial limit to a question about an appropriate or an 'acceptable condition'. It is also stated (Saarinen, 2006) that sustainable tourism should be based on a TCC according to the heritage site, tourist activities, and community perspective. Nevertheless, it is still common to trust on the TCC as a "magic number" in practice. In China, for instance, there is a set of defined TCC standards for the main tourism sites. And for the Palace Museum, it is 0.8-3.0 m^2 per person (China National Tourism Administration, 2014). For the past projects that we did in Palace Museum, we separated the TCC standard to two levels: 1) the maximum TCC relating to the first issue of impact on heritage, and 2) the suitable TCC pertaining to the perception and experience of visitors. Furthermore, for different sort of spaces, we also used different standards, for example, people in outdoor areas, psychologically, need a larger area per person compared to indoor areas.

In this paper, we follow the previous practice of two levels of TCC standards with different sorts of space, and we move one step further: the TCC would be measured spatiotemporally, i.e. along the dynamic process of touring, TCC should always be verified, leading to the "acceptable conditions" required for finer management.

2.2. AGENT-BASED SIMULATION IN URBAN STUDIES

As a bottom-up modelling approach for understanding and studying a complex system, an Agent-Based Model (ABM) or an Agent-Based Simulation (ABS) "allows one to simulate the individual actions of diverse agents, and to measure the resulting system behaviour and outcomes over time" (Crooks & Heppenstall, 2012). Due to its spatiotemporal nature and dynamics, ABMs have been broadly explored in urban studies as a tool to model the social phenomena and human behaviour (Batty, 2001). Among other things, they are effective in mapping crowd movement patterns and detecting potential risks at spatial bottlenecks for pedestrians, e.g. (Du, Guo, & Jin, 2016) shows an application of an ABM in testing the effectiveness of congestion control measures with different strategies. Our approach is similar to the latter in the sense of formulating the problem mathematically and performing a crowd simulation. However, what sets our approach apart from existing approaches is our finer spatial and temporal scale as well as our focus on the entire tour program rather than only the peaks. In this paper, we use the Thunderhead Pathfinder 2019 software application, an agent-based egress and human movement simulator originally used for evaluating the ease of escaping emergencies in public buildings, as a tool for testing our mathematical formulation of the problem and the proposed touring program.

3. COMPUTATION

3.1. TOURING PROGRAM ALTERNATIVES

At the starting point of the project, three alternative touring strategies were considered, namely free visit, human-guided tour and audio-guided tour, all of which have been applied for different areas of the Palace Museum. The free visit has been denied in the beginning by the operators, as it may go back to the situation before conservation easily, i.e. an overload of tourists, and it may not offer a meaningful experience for the visitors to take home. As for the other two options, they are both feasible to guide or even control the visitors spatiotemporally through a predesigned touring program (the highlighted spots are shown in *Figure 4*). However, while the human-guided option may lead to easier management on site, it also asks for more training costs and long-term running costs, such as the salaries for guides, which could be enormous. So, the computation here for the project focuses on the audio-guided individual visit program, which can be more economical and efficient for managers as well as comfortable for tourists.

3.2. SPATIOTEMPORAL TOURING PROGRAM

In this section we propose the following sequence of deduction to compute the optimal touring program based on the constraints and objectives in reality:

For each individual visitor, their touring program follows the same sequence T_i values, denoting the ideal stay time at the i_{th} spot. However, for the j_{th} visitor, they may not follow exactly the allocated time. Therefore, the cumulative time spent for each visitor j at location i, denoted as $M_{i,j}$ will differ after visiting i_{th} spot, according to the following equation, with some normally distributed error $\epsilon_{i,j}$:

$$M_{i,j} = M_{i-1,j} + T_i + \epsilon_{i,j}, where : \epsilon_{i,j} \tilde{} N\left(0, \sigma_i^2\right) \quad (1)$$

We can assume the lag time for any visitor to start the tour is the same value τ. The j_{th} visitor will be staying at spot i within the range $r = \left[\tau j + M_{(i-1,j)}, \tau j + M_{(i,j)}\right]$, counting from the moment the first visitor started. At any moment in time denoted as t, the number of visitors staying at the spot i is the cardinality of the set of all visitors j that fulfil the following condition: $t \in r$.

The earliest and the latest persons who could still be present at the i_{th} space at time t, are respectively denoted as j_e and j_l, and can be found by solving the following equations:

$$t = \tau j_l + M_{i-1,j_l}, t = \tau j_e + M_{i,j_e} = \tau j_e + M_{i-1,j_e} + T_i + \epsilon_{i,j_e} \quad (2)$$

However, we only need to find the difference between these two ordinal indexes j_e and j_l, in order to find the capacity of the i_{th} spot as the number of visitors N_i which could be staying at spot i at any moment t:

$$N_i = j_l - j_e = \frac{T_i + \epsilon_{i,j_{\min}} + M_{i-1,j_{\min}} - M_{i-1,j_{\max}}}{\tau} \quad (3)$$

To make it easier for getting an initial draft touring program, we could assume that every visitor stays at the i_{th} spot, precisely following the allocated time, denoted as T_i, or that the deviations sum up to 0. Then the equation above could be simplified as $N_i = \frac{T_i}{\tau}$. We could then formulate the problem as maximizing the total number of daily visitors V as a function of the lag time τ, the allocated times per spots T_i, and the daily opening time duration T_d, i.e. the manager can tune these three variables such that the overall throughput V could be maximized:

$$V(\tau, T_i, T_d) = \frac{T_d - \sum_i T_i}{\tau} \quad (4)$$

Subject to the following constraints, where A_i denotes the area of the i_{th} spot and C_i denotes the TCC standard capacity of that spot, and T_m means the minimum acceptable duration of visit:

$$N_i = \frac{T_i}{\tau} \leq \frac{A_i}{C_i}, \sum_i T_i \geq T_m \quad (5)$$

We can calculate the baseline allocated staying time T_i for each spot as $T_i = \tau \frac{A_i}{C_i}$; and compute the lag time $\tau = \frac{T_m}{\sum_i \left(\frac{A_i}{C_i}\right)}$.

The procedure above is probably an over-simplification biased towards considering the best-case scenario, i.e. a scenario in which all visitors precisely follow the tour within the allocated times, which clearly ignores the cumulative effect of the deviation $\epsilon_{i,j}$. In the real-world situation, this value could be very large in the worst-case scenario, so we do need a stochastic simulation model to verify the results.

As is suggested by the previous sections, we have set both the maximum and the suitable TCC standards differently for each highlighted spot according to their position (outdoor, roofed, and indoor) and importance. Bearing the issue of underestimation in mind, we choose to use the suitable rather than maximum TCC standard here, to give flexibility to the system.

The result of the computation is shown later in *Figure 4* as the mean staying time for each highlighted spot. The optimal lag time to start the tour τ is 6 seconds, which leads to an overall daily number of visitors V being 4,200.

3.3. PEAK CONTROLLING FOR TOURIST FLOW

The result of computation leads directly to a dilemma here, i.e. the optimal lag time for people to start the tour τ, is almost impossible to be implemented in practice: i.e. for operational reasons, it is only possible to admit tourists within a time-window, for example, if we issue a ticket for entry from 10:30 AM to 10:45 AM, the length of this time window will be 15 minutes, which is still far larger than the scale of τ. If we assume that the inter-arrival of all the 150 people who reserve to enter the Hall in a reservation period follows a Poisson or exponential distribution, it may still cause peaks and valleys of the tourist flow, which is neither good for the heritages nor efficient for the managers. Thus, we could take one step backward: rather than ensuring the starting time of the entire tour with a lag time τ, we could promise the frequency of entering the inner yard by setting several check-points in the outer yard to tune the flow gradually, like the water gates. Then the outer yard would function as a buffer zone to smoothen the peaks and valleys. Under such a principle, we could set a looser touring program for the highlighted spots in the outer yard, with relatively larger σ_i, i.e. wider span of likely error $\epsilon_{i,j}$, and thus give visitors more freedom to choose their own pace and explore the exhibitions themselves before entering the more deterministic space. The positions and the effects of each check-point are shown in *Figure 4*. The flow rate control could be realized by setting either an electric door or a brake at each entrance with a single adjustable operational frequency.

There is another issue that we have not discussed so far: if we designate a few check-points to smoothen the peak of tourist flow, then there will be queuing at these points and thus the check-points need to have the spatial capacity to hold people. For each check-point, we could allocate a queuing scheme for a time-window of 15 minutes. The inter-arrival times will follow an exponential distribution and correspond to the flow rate before and after the check-points. Theoretically, we could readjust the flow rate sequence and the number of staff needed handing out audio guide by computing the queue lengths and mean queuing times for each check-point according to Queuing Theory Models (Hillier & Lieberman, 2015, chapter 17), and/or Discrete Event Simulations (ibid, chapter 20) in Operations Research. However, in this research, we will achieve the goal, among the others, through an Agent Based Simulation Model.

4. SIMULATION

4.1. SIMULATION SETTINGS

We use the Thunderhead Pathfinder 2019 for running a crowd simulation to test our touring program. The assessment starts with manually setting input parameters for the model, which include the generation rate of the agents, the simulation length reflecting the real-world time range, the behaviour sequences of the different agent groups, the mean, variance, and probability distribution function of the staying pattern of the agents for each spots, and the entering directions and maximum flow rates of the gates. The output of the simulator includes a 3D animation showing the agents' movement and instant density along the simulation period all around the building, the route and staying time for all the agents (as is shown in *Figure 1*), as well as the occupancy of all the rooms or subspaces and the count of bypassing agents through all the gates as a function of time.

For the first simulation, we set the parameters based on the results of previously estimated parameters. The generation rate of the agents into the system follows the theoretical arriving pattern, i.e. a Poisson distribution with a periodicity of 15 minutes. The simulation lasts for 7200 seconds with a status update timestep of 0.25 second, demonstrating the first half hour at the beginning of the day when the first groups are arriving, the last half hour during the end of the day when the last groups are leaving, and in between, at a typical hour when the system is in balance with arrivals and leaves. The agents follow a movement sequence as is suggested by the proposed touring program above, with mean staying time according to the allocated T_i, and the variance of the staying times of the individuals obeys a normal distribution $N\left(0, \sigma_i^2\right)$. The freedom while visiting the outer yard is larger than inner yard with a larger ratio of $\dfrac{\sigma_i}{T_i}$. In order to prepare for the real-world situation in the worst case, we allow 5% of the agents to behave abnormally, with significant longer staying times and larger variances at most of the spots. We also set the maximum flow rates of the check-point to test the effect of peak control on queuing.

4.2. ADJUSTMENTS FOR THE TOURING PROGRAM

As we run the simulation with the initially proposed touring program based on estimated parameters, we can observe from the animation and the recorded data if the program is feasible. An infeasible program would result in the collapse of balance at certain spots, suggested by unbearable growth of the number of agents in the allocated space of that spot, which means long queues or even getting stuck for visitors and overload for the heritage. A touring program can be thus adjusted and improved to be more resilient to the possible worse cases by means of: 1) shortening the staying time T_i for the problematic spots, 2) narrowing or broadening the tolerance of variance σ_i^2 for some regions, and/or 3) increasing the number of staff at the check-point where audio guides being handed out.

After several rounds of simulation and adjustments, we managed to keep the performance of our touring program in all spots reasonable at all time, meeting all the pre-set objectives, which will be discussed in the next section.

4.3. VERIFICATION

Based on the discussion with the operator of the Palace Museum, we mainly needed to verify three management objectives with our agent-based simulation model for the touring programs: 1) not crossing the uncomfortable line of density based on tourism carrying capacity for any spot at any time; 2) the peak caused by arriving periodicity being finely controlled and smoothened along the tour; 3) no too long queues in any spot, especially for the check-points. With the results shown in Figure 3, we could demonstrate and explain that our touring program has fulfilled all of these objectives.

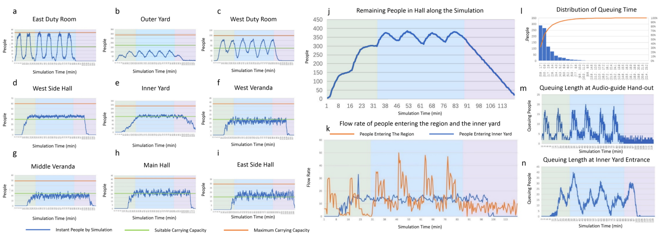
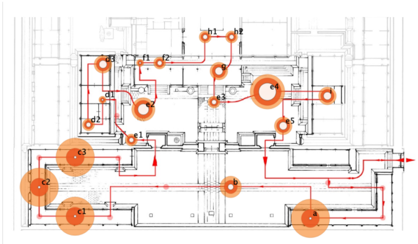


Figure 3. The results of the agent-based simulation in Pathfinder. Labels a) to i): The occurrence of agents at the space of each spot along the time-line; j) The overall number of visitors remaining in the building at any moment along the time-line; k) The flow rate of agents entering the system and entering the inner yard; l) The histogram showing the distribution of the total waiting times of the agents in the system; m) & n) The queuing status at the check-points.

In the *Figure 3a* to *3i*, we could see the simulated occupancy of each spot, with the green line showing the capacity of visitors $\frac{A_i}{C_i}$ calculated with the suitable TCC standards, and the red line showing that with the maximum TCC standards. For all the six spots in the inner yard, the number of agents fluctuates around the suitable green line along the time-line, even for the two indoor spots in the outer yard, which are strongly influenced by the periodic peaks, the number of agents also never exceeds the maximum red line. For the spot shown in *figure 3b* which is the outdoor area in the outer yard, the number of agents is even lower than the green line all the time, which suggests that there is potential to add more activities here. The balanced overall visitors remaining in the region, as is shown in *Figure 3j*, ranges from 300 to 370 during the typical moments. The overall instant number of visitors also corresponds to the traditional method of TCC calculation, which would lead to 360 to 418 concerning only one single standard for the whole region and the overall accessible area. All the arguments here suggest that the touring program always fulfils the first objective of giving both the visitor a comfortable experience and the heritage site a bearable load. As shown in *Figure 3l* and *3m*, the queuing all around the region is also not an issue, as 90% of the agents in the simulation only queue for less than 3 minutes among their entire journey of 28-38 minutes. Even for the most severe part, where audio guides are being handed out, the queue length would be less than 20 people falling under 5 people in around 5 minutes, with 3 staff members working simultaneously. Concerning the longer queues at the entrance to the inner yard (*Figure 3n*), people can relax and enjoy exhibitions in the outer yard (*3b*), which is flexible enough as a buffer zone. The results also suggest that the touring program meets the third objective of lessening queues. As is seen also above in individual spots where the influence of the periodic peaks is being weakened along the touring sequence, the effect of peak control can be seen more directly from *Figure 3k*. The number of visitors going through the main gate follows the Poisson distribution with a cycle of 15min, which shows the peaks and valleys of the tourist flow. However, after several rounds of slowing down and smoothing by the check-points, the number of people entering the inner yard remains more or less around a constant, which suggests that our peak control is successful as confirmed by the simulation.

The final touring program that fulfils all the objectives is shown in *Figure 4*, where the size of the circle visualizes the mean staying time at the spot, including the time spent with the audio guide and freely looking-around.



High-light Spots	mean(s)	min(s)	max(s)	sd(s)	audio guide duration
a. 东南值房	120	60	150	45	Free Visit
b. 外院室外空间	90	30	180	15	No less than 20s
c1. 西南值房A区	120	30	180	45	Free Visit
c2. 西南值房B区	120	30	180	45	Free Visit
c3. 西南值房C区	120	30	180	45	Free Visit
e1. 内院西侧入口	60	50	70	5	Around 50s
d1. 西配殿A展厅	30	20	40	5	Around 20s
d2. 西配殿B展厅	60	50	70	5	Around 40s
d3. 西配殿C展厅	90	80	100	5	Around 90s
e2. 内院西	120	100	130	5	90s-100s
f1. 三希堂	30	20	40	5	Around 15s
f2. 勤政亲贤	60	50	70	5	Around 50s
g. 中抱厦	90	80	100	5	Around 75s
h1. 正殿明间	60	50	70	5	Around 45s
h2. 垂帘听政	60	50	70	5	Around 45s
e3. 内院中	60	50	70	5	Around 45s
e4. 内院东	180	160	200	5	120s-150s
i. 东配殿	90	80	100	5	Around 60s
e5. 内院东侧出口	90	80	100	5	Around 60s

Figure 4. The final Touring Program after verifications and adjustments based on our Agent-based Simulation. Left: The touring route with the mean and variance of staying time on each spot denoted by circles and check-points as triangles; the glows around the circles demonstrate the variance of staying or the extent of freedom during the visit of that spot. Right: The description of each spot.

5. DISCUSSION AND CONCLUSION

As is argued in the famous quote "All models are wrong but some are useful"(Box, 1979), our simulation model intends to provide a useful guideline to support and aid the real-world heritage management; but it is not meant to predict the individual trajectories of tourists within a heritage site. The simulation may reflect the reality poorly because of the various complicated attributes that we did not consider in this research. However, the model turns out to be insightful enough to guide the exhibition planning and the management program, both of which are yet to be realized. We intend to use tracking tools after the official reopening of the hall, in order to measure the actual use and validate/calibrate our model. Our proposed methodology is not meant to replace the existing feedback control procedures; instead, it is meant to provide insight as to how the system can be used at maximum capacity, to test the limits and make planning decisions. In real-time, the managers still do need to monitor the number of people exiting to decide whether they should let newcomers and latecomers in, and whether they should encourage or even nudge the visitors forward, in particular those who have been spending 'too much time' in a specific spot.

It can also be seen from our research, that the fineness and preciseness of the program, the difficulty of realizing the management and operation schemas, the objective of a high-quality memorable visiting experience, and the need for accepting as many visitors as possible, may be contradictory with each other. However, they are all critical and crucial from different angles. This methodology may not be able to solve all of these problems and fulfil the needs of everyone. It is, however, a starting point for heritage site managers such as those of the Palace

Museum to make a new step forward towards better and more efficient heritage management, trying to find a balance point to optimize the overall experience for the stakeholders involved: managers, operators, visitors, and the heritage site, while making some reasonable trade-off instead of imprecise compromises.

We presented the utilization of an agent-based simulation model for adjusting a touring program and gave a detailed example for the Hall of Mental Cultivation in the Palace Museum of Beijing for its reopening in 2020. The model is based on a relatively novel pursuit of estimating and verifying the Tourism Carrying Capacity from a dynamic perspective. The proposed touring program seems to meet the objectives of the visiting experience, heritage safety, and management efficiency, showcasing the effectiveness of the proposed methodology for better and finer heritage management. We have estimated the optimal staying times on a number of spots for a touring program and as elaborated in *Figure 3*, the simulation results agree with both the TCC standards and our engineered touring program. The results of the research are already approved by the department heads of the Palace Museum to be implemented for planning the future exhibition programs.

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