Serious Game Design for Resilience Enhancement of Transportation Infrastructure to Cyber Threats and/or Flood Hazards

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***Abstract*—It is challenging to predict the precise location and severity of flood events, which can cause major disturbance to different public services, such as disruption to and the closure of critical transportation infrastructure. Therefore, approaches to enhance the resilience of these infrastructures are required. Serious games are new computing tools that have been applied in various fields with a combination of gameplay, learning and training. However, the application of serious games in intelligent transportation systems remains underutilized. As a result, the concept of a serious game is developed in this study to significantly improve transportation infrastructure resilience in an example of a flooding event. The serious game concept presented in this paper is being developed as part of the H2020-funded PRECINCT project (www.precinct.info).**

Keywords—Serious game, transportation infrastructure, flood, resilience.

I. INTRODUCTION

The main aim of Intelligent Transportation Systems (ITS) is to enhance transportation mobility and safety, as well as improve the integration of advanced technologies into the transportation infrastructure [1]. Critical Infrastructures (CIs) in transport include airports, bridges, tunnels, roadways, ports, etc. can be subjected to damage induced by different causes such as fatigue, aging, environmental effects, overloading, flood, earthquake, wind excitations or terrorism and criminal activities during their service life which can critically disturb their integrity, serviceability and safety [2]–[5]. CIs within urban environments, such as transportation networks, energy networks, communication networks, etc. are influenced by each other due to their interdependencies. These interconnections result from the integration of smart infrastructure and the reliance of each infrastructure on other infrastructures to function, i.e. a transport network needs the energy network and communication network to function. As mentioned above, these interdependent CIs can be damaged due to physical threats or hazards, e.g. a flood. In this context, the frequency and severity of climate-driven natural hazards seem to be rising in the European Union's countries [6]. In addition to the increased severity, hydro-meteorological events such as storms, floods, and landslides have a significant impact, and account for 64% of the reported damages due to natural disasters in Europe since 1980 [7]. The knowledge and experiences of Critical Infrastructure Operators (CIOs) when dealing with such hazards, are primarily limited to the sectoral CIs for which they work. ITS are not only susceptible to physical hazards such as flooding, they are also susceptible to cyber threats, e.g. denial of service attacks. However, understanding the interdependency and cascading effects of CIs to complex cyber-physical threats is essential for improving the resilience of ITS. The resilience assessment of CIs is challenging due to the various influencing elements as well as the complex mechanisms in the interlinked smart systems of CIs. It is a challenge to have an overview of the influence of all interdependent CIs. Consequently, this paper presents a novel serious gaming approach, incorporating the interdependency, cascading effects, and resilience scores of CIs to address the current deficiencies. Additionally, the serious game aims to prepare CIOs better to respond to such hazardous events within an 'edutainment' environment. The serious game concept presented in this paper is being developed as part of the PRECINCT project (www.precinct.info). PRECINCT stands for Preparedness and Resilience Enforcement for Critical INfrastructure Cascading Cyber-Physical Threats, a European Union's Horizon 2020 funded ongoing project.

It is worth noting that serious games are relatively new technology-enhanced simulation tools developed for a purpose other than entertainment, such as teaching a specific knowledge or skill. Unlike traditional approaches, they are often considered to provide a more interactive learning environment, a motivational approach to learning, and safe training for patients and students [8]. In recent years, research on serious games has increased significantly. They have recently emerged in the educational game market with the combination of play and learning [9]. A wide range of serious games has been used in various fields such as psychology, medical, dental, energy, language learning, etc. However, the application of serious games in intelligent transportation systems remains underutilized.

II. ENVIRONMENTAL EFFECTS OF FLOODS

A complex combination of factors, including climate change, land-use change, poorly implemented regulation, and a lack of integrated planning, has often resulted in environmental degradation and disproportionate impacts of natural disasters affecting millions worldwide [10]. Flooding events (surface or coastal) can destroy buildings, roads, bridges, and trees, devastate agriculture, cause mudslides, and threaten human life [11]. Flooding hazards account for almost half of bridge failures for a range of factors, i.e. (1)

scour at the foundation, (2) hydrodynamic loads and pressures on the deck, piers and/or foundations, (3) overtopping, and (4) debris accumulation [12], [13]. Therefore, in the recent decades, several strategies have been introduced, developed, and implemented to manage the environmental effects of floods as well as control the safety of transportation infrastructure. For example, a wave monitoring system was installed on the National Highway in Japan in order to detect the direct and indirect impact of floods on the transportation sector [14]. Moreover, different flood detection systems have been proposed, accordingly [15].

III. Background and Overview of Serious Game

Gamification can be defined as "using game-based mechanics and theory to engage people, motivate action, and promote learning" [16]. In 1987, the term ''serious game'' was introduced by researcher Abt [17]. In 2002, the US Army developed a serious game in the form of a video game named America's Army. Then, the Serious Game Initiative was founded in 2002 by the Woodrow Wilson Center for Scholars in Washington, D.C. [18]. They described serious games as ''games that do not have entertainment, enjoyment, or fun as their primary purpose'' [19]. In other words, a serious game is a computer-based simulation that merges knowledge and skills development with video game-playing aspects to enable active, experiential, situated and problem-based learning. Nevertheless, ''entertainment'' has been considered a significant factor of serious games in other definitions, e.g. ''serious game is a mental contest, played with a computer in accordance with specific rules, that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives'' [20]. It can explore entertainment for different purposes, such as training, education and skills development [21]. Since 2002, serious games have been successfully introduced for different domains such as education, scientific research, environmental science, healthcare, government, politics, military, entertainment, religion, security, marketing, culture and art [22].

According to a recent report entitled "Serious Games Market by Gaming Platform, Application, Industry Vertical, and Region: Global Opportunity Analysis and Industry Forecast 2021–2030", the serious games market was valued at $5.94 billion in 2020 and is projected to reach $32.72 billion by 2030 [23]. The authors of [24] proposed the main characteristics of a serious game, as follows:

- An action language for communication between game and player;
- Assessment tracks the number of correct answers;
- Conflict or challenge;
- Control, or the ability for the players to alter the game;
- Environment;
- Game fiction or story;
- Human interaction among the players;
- Immersion in the game; and
- Rules and goals of the game provided to the player.

The serious game presented in this paper aims to improve the resilience of transportation infrastructure in an example of a flooding event.

IV. Interdependency Graphs and Cascading Effects

CIs are increasingly at risk from various intentional cyber-physical attacks and risks from natural hazards. However, assessing and managing the impact of cascading effects arising from the interdependencies between different types of CIs and different types of hazard/threats and their resilience for 'rapid recovery' is becoming increasingly pertinent and is highly challenging, especially in the context of delimited geographical areas (e.g. districts, cities or regions). The vulnerability of urban centres points to the need for public-private solid coordination to mobilize a response from different sectors and an improved level of protection for associated CIs [25].

Understanding the various effects of an incident such as a flood requires knowledge about the hazard, the area and infrastructures that will be affected. Modern CIs are strongly interconnected, and the reduced operation of one or more may affect others. Therefore, a profound threat analysis includes awareness of the relevant CIs and their interdependencies. In this paper, these interdependencies are modelled through a graph where nodes represent CIs (or relevant parts of CIs), and edges represent dependencies, such as exchanging of resources or providing services. A generic example of such a dependency graph is shown in Fig. 1. Several components of a water utility, telecommunication provider, power provider, hospital, traffic, and emergency services are shown with the dependencies between them. A threat may affect these CIs and indirectly influence people living in the area, which is a core aspect of the analysis. The dependency graph provides an awareness of potential indirect dependencies and enables the simulation of how an incident may affect such a network. The degree to which a component is affected by a threat can be interpreted as the level of functionality or availability of the respective CI. Different nodes react in different ways to a specific threat, so it is necessary to describe the dynamics of each node through an individual "inner" model. The approach here uses Mealy automata models [26], as these describe reactions to an incoming alarm (e.g. notification of a sensor) and inform dependent nodes in case the functionality or availability of the node changes due to that alarm. Knowing the local reaction to a cyber-threat and/or physical hazard, i.e., how the state changes due to a specific threat and/or hazard, the simulation allows an estimation of the global reaction of the entire network. The interdependencies between CIs, including their links to emergency services and transportation, need to be addressed more holistically to increase the safety and security of citizens.

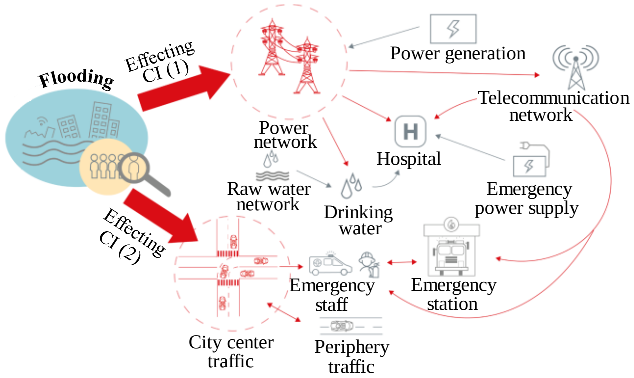

Fig. 1. An example of dependency graph [27]

V. Resilience Calculation

Over the past decade, the concept of resilience has rapidly evolved in the context of CIs. Within the PRECINCT project, a review of recent work in the space of resilience was carried out to identify a strategy for resilience calculation. The following definition for resilience was adopted:

"Resilience is the ability to continue to provide service if a disruptive event occurs"

The PRECINCT project builds upon work which has preceded it in order to define a quantitative Resilience Methodological Framework (RMF) which defines a Resilience Index (RI) based on a monetary representation of the losses due to break down in the service provided by the CI. Some examples of service measures are provided below for different CIs:

- Railway network: Passenger miles, ticketing.
- Road network: Delay times, safety of road users.
- Electricity/telecom network: Availability of power.

Service measures tend to vary from one CI type to the next. The monetary estimation used within PRECINCT allows summation of all service measures involved in the assessment of a multi-modal CI.

In order to describe the resilience-relevant parts of the CI, "resilience indicators" are used. These are separate aspects to the RI, as they are essentially representative parts of the CI which indicate how resilient the CI is to the posed threats. Resilience indicators may be classified as Infrastructural, Environmental or Organisational. Each indicator is assigned a score based on the baseline state. Table I provides some examples of indicators for a specific CI consisting of various infrastructure types. The various potential states of each indicator are listed in the table, as well as the context/meaning of each state. Wherever possible, the indicators states should be based upon existing standards and codes of practice relating to the indicators. For example, the indicator states for "Bridge Condition" may be based upon the states listed within the inspection protocol already in place for the bridge.

Table I also indicates the state to which the indicator impacts the resilience of the system. For example, the "Bridge Condition" indicator impacts the "Absorb" phase of the resilience cycle, as a higher bridge condition increases the resistance to a triggering event (e.g. flood and earthquake), while the "Number of City Police" impacts the "Recovery" phase. That is, more police mean that the after effects of a triggering event can be limited, bringing the service back into place more quickly.

Once the resilience indicators have been assigned, their impact on the service measure for a given triggering event must be determined. In this respect, the RMF works in conjunction with the interdependency graph simulation described in section IV. Each indicator may be modelled as a node within the graph. In this way, the impact of changes to the indicator values can be modelled, considering the interconnected and time dependant nature of the problem. By simulating the various outcomes of indicator changes, the relative weight of each indicator on the service can be determined. The service measure used to quantify the resilience can also be determined from the cascading effects simulation as monetary values can be assigned to the output state of the nodes which are related to the service provided. This output data can then be fed to the back end of the serious game in order to allow users to investigate the impact of various combinations of actions taken before, during and after a hazard/threat event. Cost benefit assessment can be combined with machine learning algorithms in order to train models to predict optimum strategies for the various actions that can be taken, subject to budgetary constraints.

TABLE I. Sample Resilience Indicators

Part	Indicator	Phase	Possible values	Meaning
Infrastructure	Telecom ICS Protection Systems (firewalls)	Absorb	4	State of the art
			3	Slightly outdated
			2	Very outdated
			1	Not in place
	Bridge Condition	Absorb	5	Like new
			4	Slightly deteriorated
			3	Average
			2	Poor
			1	Alarming
	Rail control centre backup power supply	Recovery	3	Automatic back up
			2	Manual back up plan
			1	No back up system
Environment	Ease of physical access to Telecom staff area	Absorb	5	Very low risk
			4	Low risk
			3	Average risk
			2	Moderate risk
			1	Severe risk
	Accessibility of bridge infrastructure	Recovery	4	Fully accessible after event
			3	Fully accessible with specialist equipment
			2	Semi-accessible
			1	Not accessible
Organisation	Telecom staff crisis training	Recovery	3	Constant training
			2	periodic training
			1	no monitoring
	Monitoring of threat level	Absorb	4	Every week
			3	Every month
			2	Every 3 months or more
			1	No monitoring
	Number of city police staff	Recovery	5	more than 200 staff
			4	150-200 staff
			3	100-150 staff
			2	50-100 staff
			1	less than 50 staff

VI. Serious Game Architecture, Components, and Process

The proposed serious game uses initial pilot data and concepts from flooding events in a city PRECINCT, which offers interactive decision support and scenario specification/building user interface that the player interacts with when gaming. Fig. 2 and Table II summarize the flowchart, interface, principal components, and elements of the proposed PRECINCT serious game, respectively. The game's concept design can be seen in Fig. 2. Firstly, a registered user logs in by entering their username, email, and password, then selecting a character, either the Game Director, an Attacker or Defender. Once a user is logged in, the game will present the qualified director with a director's dashboard to select the type of physical or cyber-attack, the location, and the budget for the attacker and the defender for each CI. The attacker's dashboard enables the attacker to select tools for the initial attack, use upgrade tools for changing the severity of the hazard or threat, and utilise noise to generate small attacks aiming to confuse the player. The defender will be presented with the game's initial budget balance, the player's ranking, the attack type and the level set by the director. Next, the defender must enter his or her job role and the number of years of experience in this position.

The game director will be a trusted member of staff from the CIO or else emergency response coordination team.

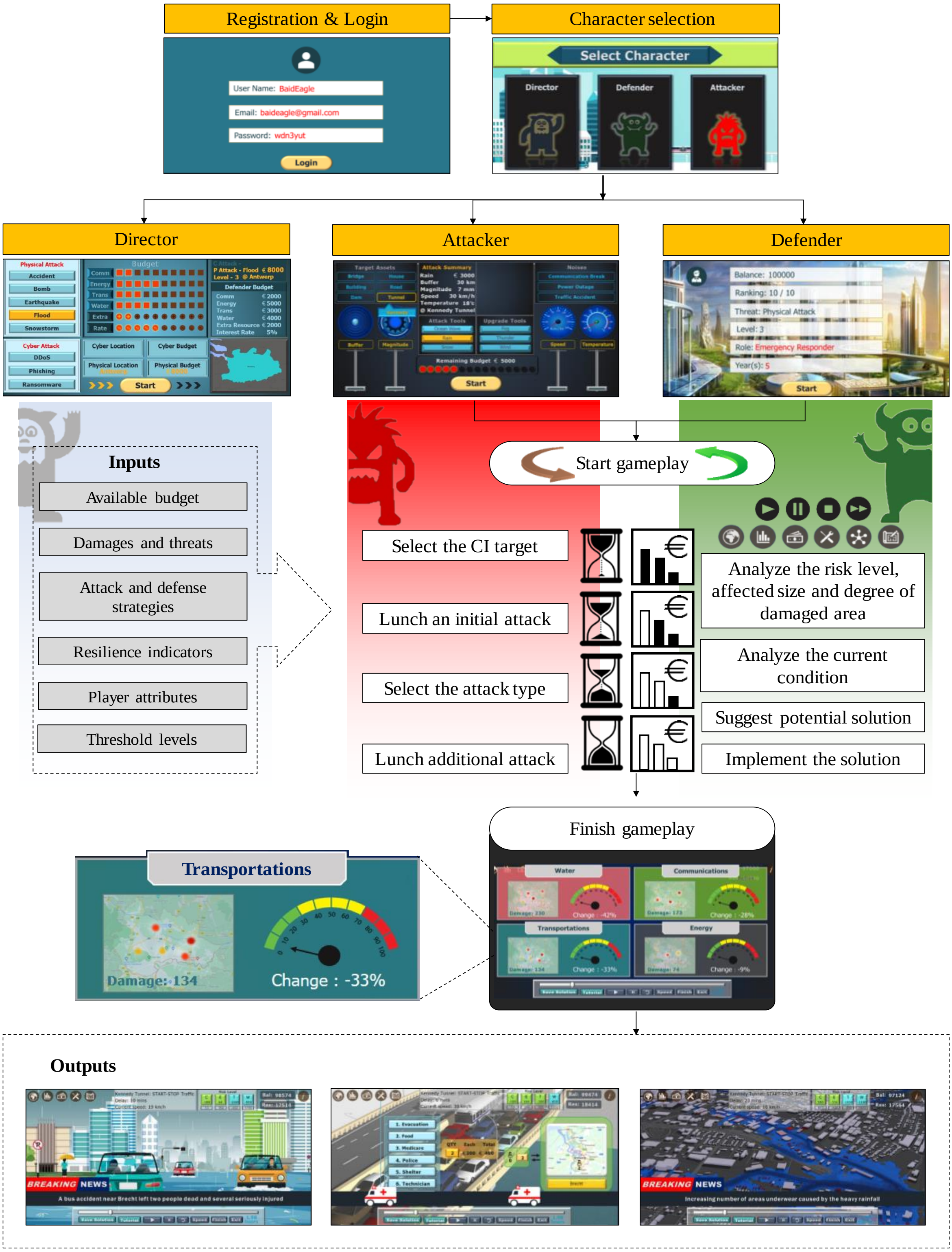

Fig. 2. Flowchart of the proposed serious game along with game interface

Next, the defender is presented with the opening attack scenario: flooding set by the director using the rainfall selected by the attacker to launch the initial attack. The game provides a set of analysis tools to help the defender understand the impact of the hazard, through geospatial visualization, the CI's resilience rating, and traffic data, for example. The game uses the interaction of the attacker and the defender to simulate an attack's cascading effect. After the defender implements a solution to counteract the attacker's first attack, the attacker can intensify the attack by increasing the severity of a rainfall event, for example. Consequently, the transportation infrastructure is damaged due to the additional attack. The size of the affected area, the resilience rating for each CI, the links of affected CIs, and the detailed cascading effect between different CIs can also be displayed using the proposed serious game.

TABLE II. LIBRARY OF COMPONENTS OF THE PROPOSED SERIOUS GAME

Characters	Dashboards and Roles
Director	- Setup damage scenario(s), i.e. type of attack and location (Damage identification) - Define budget for defender and attacker for each CI
Attacker	- Select the CI target (Damage location) to lunch an initial attack - Select the attack type (Damage severity) - Can lunch additional attack by selecting destructive option(s) or increasing the severity of damage
Defender	- Provide the player's information, i.e. the initial budget balance, ranking, type of threat, job role, years of experience - Select gameplay options to play, pause, restart, speed or quit the game - Use the provided tutorial, control elements, time slider and play buttons - Finish the game and get the report (game score)

Control Elements Information	
1 Map button: Geo spatial analysis - Provide the geospatial visualization based on: ▪ Damage location (Affected size) ▪ Damage severity (Degree of damaged area) ▪ Level of Resilience	4 Tool button: Potential solutions - Suggest suitable action(s) such as: ▪ Warning/Evacuation ▪ Sending Food, Medicine, etc. ▪ Police patrolling ▪ Sending technician(s) for maintenance/repair ▪ Providing Shelter
2 Analysis button: Current condition and analysis - Present the following updates: ▪ Interdependency graph (Model of linked CIs) ▪ Risk level and affected size (Damage detection) ▪ Resilience meter	5 Sub-CIs button: - Present the relevant sub-CIs, e.g. ▪ CI: Water (Damage type: Flooding) ▪ Sub-CIs: Drain, Reservoir, Sewer
3 Additional resources button - Allow to requests limited additional budget with an interest rate	6 Bookkeeping button: Expenses distribution - Allow to implement the aforesaid potential solution(s) in tabular or map-based format - Allows to enter the amount of expenditure for each CI

VII. FUTURE WORK

The proposed serious game system architecture in this paper was designed to improve the resilience of transportation infrastructure. The development of the serious game will begin in the next phase of the PRECINCT project. The serious game tool contains the main serious game application, which will be the user application running on a Windows operating system either as a native application or as a web application, and the middleware component supporting/hosting the serious game and connecting it to a PRECINCT digital twin. Developing serious games utilising the interdependency of infrastructure's resilience reflecting a more realistic representation of real-life attack scenarios resulting in more sustainable smarter cities. Therefore, our future work aims to improve CI resilience using a serious gaming approach to train CIOs and emergency responders to improve responses to physical-cyber-attacks.

VIII. CONCLUSION

In this study, a serious game concept design has been developed focusing on enhancing the resilience of transportation infrastructure. The gameplay starts with user registration and login. Then, the gameplay was presented, and finally, the analysis of the gameplay was briefly discussed. Based on the provided details, the following conclusions can be drawn:

- The serious game presented in this paper allows players to realistically and accurately represent their transportation infrastructure within a gaming environment.
- A geospatial analysis of the urban area under consideration in the game enables players to visualise the problem's domain and all interconnected /interdependent CIs.
- The role of the game director is to select the type of attack, the location and the budget for the attacker and the defender for each CI (e.g. transportation, energy, or telecommunications network nodes).
- The game players (attackers and defenders) can investigate the impact of different severity of flood events or different types of cyber-physical threats on the transportation infrastructure as well as their interdependencies and cascading effects through different game metrics, particularly resilience.
- Game players will have full control of the game without providing the assumed best response strategies to particular hazards/attacks.
- The focus of the proposed serious game is to help CIOs understand their current resilience to cyber-physical threats, improve their response and recovery processes and prepare for unseen events, thereby improving the resilience of CIs and their operators to unforeseen attacks or natural events.
- PRECINCT will implement the proposed serious games within four living lab urban areas to perform vulnerability assessments both at individual CI and at the 'command' coordination level.

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