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Article

Transdisciplinarity in Serious Gaming Design for Improved Crisis Preparedness

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Abstract

Transdisciplinarity is identified as an important paradigm to cope with the complexity of societal problems, such as public health crisis and climate change. It refers to problem solving and research strategies that integrate the knowledge from diverse disciplines to ensure a holistic approach. In the aftermath of the COVID-19 pandemic, emergency management organizations are increasingly incorporating serious games to enhance their preparedness and readiness activities. While some serious games have been used within wider transdisciplinary studies, literature reviews show that the games themselves do not exhibit a sufficient degree of transdisciplinarity. In this paper we present the theoretical approach we introduced to support the integration of transdisciplinary knowledge into the design and development of SGs looking at socially relevant problems (i.e., decision-making during epidemic outbreaks) and we show how we applied the proposed framework to design the Command, Control, Coordination, and Communication (C3C) Game. Finally, we describe the positive results from a pilot exercise conducted using the C3C Game with public health, healthcare coalition and emergency response decision makers from a large US metropolitan area.

1. Introduction

We are experiencing a surge of interest from emergency and crisis management organizations in the use of serious games (SGs) as an intervention to enhance preparedness and readiness activities. SGs are games, whose primary purpose is not entertainment [1]. They have largely been used for training and education purposes, but also as an analytical and research method or to raise awareness [2]. Some emergency management organizations have started to include them as a specific category of preparedness and readiness discussion-based exercises. For example, the United States Federal Emergency Management Agency (FEMA) defines them as "a structured form of play designed for individuals or teams. Players are guided by clear rules, data, and procedures for its execution. These games are designed to depict an actual or hypothetical situation to ensure that the participants make decisions and take actions that would be plausible.” [3]. These exercises are generally used to: (i) reinforce training, (ii) stimulate team building or (iii) enhance operational and tactical capabilities [3]. For example, SGs can be used as a means to produce new knowledge on how different groups behave and take decisions in specific situations (i.e., SGs for data collection and analysis).

There is a growing call for transdisciplinarity to address many of the unprecedented worldwide crises and societal challenges [4], such as climate change [6], chronic disease management and public health issues [5], ranging from traditional to more contemporary ones (e.g., extended healthcare downtime due to cyber-attacks). A recent analysis [7] shows how transdisciplinarity is increasingly mentioned as a way to gain integrated knowledge, which is key to address the complexity and ill-defined nature of socially relevant problems. Transdisciplinarity appears to be an appropriate approach, because of its unique ability to [8]: (i) explore the complexity of the problem, (ii) account for the different perspectives and perceptions of science and real-world, including policy and political aspects, (iii) connect abstract knowledge to case-specific one and (iv) generate new knowledge that is in line with perceived common good.

Although the term transdisciplinarity has been introduced in the 1970’s, there is not yet an agreed definition. However, there is agreement regarding the aspect that transdisciplinarity moves beyond approaches in which multiple academic disciplines look independently at the same problem (i.e., multidisciplinarity) or approaches in which multiple disciplines attempt to harmonize the links between themself (i.e., interdisciplinary), while looking at the problem from their individual perspective (Figure 1). Transdisciplinarity aims at crossing both disciplinary and sectoral boundaries, ensuring that the scientific knowledge is fully integrated in innovative ways into a unified view with the values, knowledge, know-how and expertise from non-academic stakeholders [9, 10, 11]. Analyses show an overall dichotomy between a theoretical and practical perspective on transdisciplinarity [7]. In the last two decades, transdisciplinarity has emerged as a discipline out of the efforts to harmonize methodologies and theories to reconcile the two perspectives [7]. The discipline appears to be strongly grounded on the broader field of integration and implementation science [7].

SGs are used in transdisciplinary as elements of wide research or educational efforts, but demonstrate only a partial interdisciplinary approach to knowledge (e.g., social science and natural science knowledge) in the design of the game itself [12]. This limits the ability of the SGs to move beyond the discipline perspective towards the desired integrated perspective required to appropriately address societal issues. For example, a recent review of games for health [13] has highlighted that the degree of stakeholders’ participation in the development and implementation of the SGs is very limited.

This paper addresses these two components and presents the theoretical approach we introduced to support the integration of transdisciplinary knowledge into the design and development of SGs focusing on socially relevant problems. The approach follows the model-driven design framework proposed in [21] and shows how transdisciplinarity can be integrated throughout the process, with a special focus on the creation of an SG conceptual model, which becomes a means to merge and harmonize diverse knowledge and disciplines.

The knowledge is acquired and structured through the adoption of community-centered design principles and human factor engineering techniques, such as hierarchical task analysis (HTA). We explain how the proposed framework was first operationalized in the creation of SGs aiming at improving decision-making processes during crises (i.e., epidemic outbreaks) and present the results of a first pilot. Specifically, we present the Command, Control, Coordination and Communication (C3C) Game, which focuses on C3C that are essential functions in every emergency management activity. In fact, the COVID-19 pandemic crisis highlighted the complexity and fragility of the response structure to perform and sustain these functions in large scale and prolonged events.

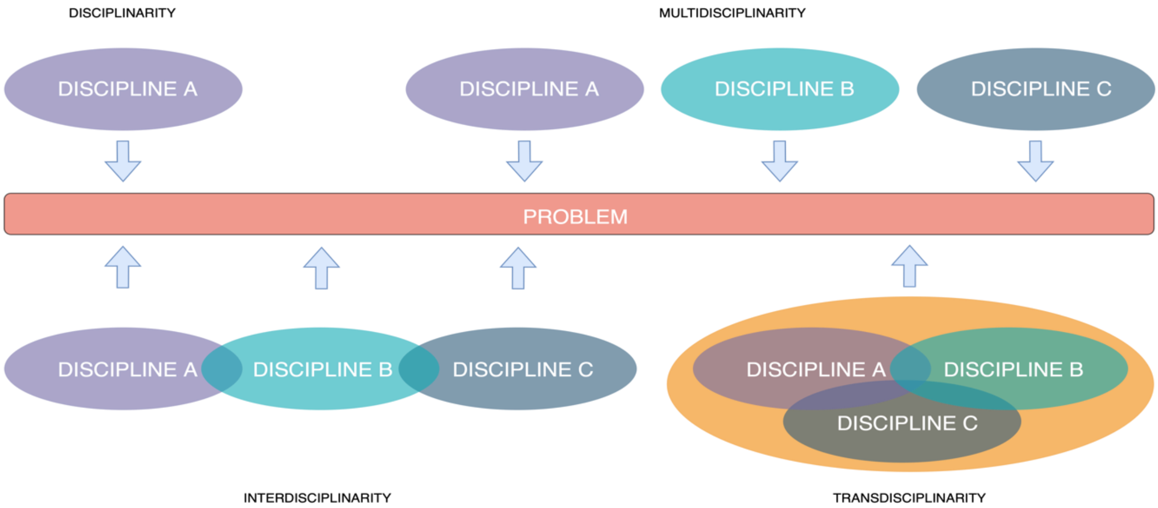

Figure 1. Representation of disciplinarity, multidisciplinarity, interdisciplinarity and transdisciplinarity concepts (adapted from [11]).

The remainder of the paper is organized as follows: Section 2 summarizes relevant work on serious games; Section 3 describes the proposed approach to achieve transdisciplinary integration into SG design; Section 4 introduces the C3C Game; Section 5 presents the results of a first exercise employing the C3C Game and Section 6 reports the conclusions.

2. Background

2.1 Crisis management and Public Health Serious Games

Several crisis management and disaster relief serious games have been developed in the last few decades, as described in literature reviews [22, 23, 24]. They have focused on different: (i) types of crises (e.g., fires, terrorist attacks, mass casualties and natural disasters), (ii) phases of the crisis management cycle and (iii) types of target audience (e.g., professionals or the public). In most cases they serve as educational and engagement tools for affected communities, policy-makers, and other stakeholders [24]. Often, they aim at improving rescue operations proficiency [23], for example by enhancing spatial thinking [25]. Some games focus on improving team coordination (e.g., [26]), procedures knowledge (e.g., [27]) and ethics in rescue operations (e.g., [28]). With respect to health, most SGs appear to target healthcare, rather than public health. Existing SGs for public health are looking at infectious disease outbreak to improve preparedness or guide behavioral change. Examples include SGs to: (i) stimulate critical reflection on gender-based factors of preparedness and response [29], (ii) explore attitude change in local population towards neglected and emerging infectious tropical diseases [30], (iii) improve safety and preparedness of targeted segments of the public (e.g., children) [31] and (iv) induce behavioral change on dental public health [32] or anti-smoking [33]. Public health in the last several decades has faced major challenges, such as climate and health crises, conflicts, wars, social inequalities and a high burden of communicable and non-communicable diseases [5]. Therefore, the community is looking with growing attention to transdisciplinary approaches, but current SGs for public health exhibit limited transdisciplinarity [12]. While literature reviews acknowledge a gap in the understanding of participatory approaches using SGs for public health (e.g., [13]), they have identified SGs as an important element supporting participatory research in the form of citizen science. In citizen science the public or non-expert audiences support the research by: (i) providing computing power, (ii) collecting, analyzing and interpreting data or (iii) co-creating the research questions and designs [13]. SGs have successfully been used to support global disease surveillance [34], providing collective diagnosis of malaria (e.g., [35]) or to improve localized participatory epidemiology through the mapping of health-related behaviors in different communities [36]. Sound decision-making to support command and control functions at tactical, operational and strategic level is key to the success of emergency and crisis management. In the military domain there is a strong emphasis on this topic and several SGs for training and analysis have been developed, for example, to explore new decision-making paradigms for multi-domain operations [37]. On the contrary, SGs for public health and other fields with a strong emergency management component have devoted little attention to this aspect, with little exceptions such as training SGs on hospital emergency management (e.g., [38]) or fire-fighting (e.g., [26]).

2.2 Knowledge Acquisition Analytical Games

The Command, Control, Coordination and Communication (C3C) Game is a Knowledge Acquisition Analytical Game (K2AG), developed as part of a US federally funded project on Predictive Intelligence for Pandemic Preparedness (PIPP). K2AG is a gaming technique used and validated in previous exercises focusing on maritime security and safety emergency management (e.g., Reliability Game [39], MARISA Game [40] and MUST Game [41]) and on the use of innovative data sources for pathogen threat surveillance (e.g., PSA Game). K2AGs are serious games that explore the underpinning processes that lead to a certain decision and action, with a special focus on the role of information and uncertainty in the decision-making cycle. To this end, the players' decision making is unfolded following human-factors models. Following Endsley [42], the decision-making process is divided into three main building blocks: situational awareness, decision and action. These are directly linked to game elements and game mechanics. These games have proven useful to steer innovation. For example, the data collected through these games enabled the extraction of reasoning patterns of players to train high-level information fusion algorithms for decision support systems [43] and to better understand future context of use of emerging and disruptive technologies (i.e., artificial intelligence and autonomous systems) [44]. Previous K2AGs have focused mainly on situational awareness and partially on the decision component. In fact, they explore how the players process uncertain information to build a mental situational picture. Specifically, participants are requested to perform threat assessments and reflect on how these assessments affect the propensity towards some of the possible response options. The C3C Game, instead, extends the scope of previous K2AGs by increasing the factors tracked and analyzed during gameplay both in relation to the players' situational awareness (i.e., vulnerability assessment and impact assessment) and decision (i.e., declaration of emergency, activation of emergency operation centers and setup of specific command, control and coordination structures). Moreover, due to the nature of the problem under consideration (i.e., a pandemic crisis) the game design had to be enriched with transdisciplinary approaches to better cope with the complexity of public health crises.

2.3 Task Analysis and Serious Games Design

Task Analysis is a family of human factors engineering approaches used to understand and represent tasks performed in specific domains (e.g., duration, frequency, allocation and complexity). It focuses both on the physical actions and the cognitive processes that are used or should be used under specific circumstances to achieve an identified goal [45]. Two widely adopted approaches are Cognitive Task Analysis (CTA) and Hierarchical Task Analysis (HTA). CTA is focusing on the knowledge structures that capture a description of the knowledge that experts use to perform complex tasks [45]. Hierarchical Task Analysis (HTA), instead focuses on how users work to achieve their goals (i.e., the tasks they perform). In HTA, activities and workflows under analysis are modeled as a hierarchy of goals, sub-goals, operations and plans [45]. Higher levels of the hierarchy correspond to more abstract concepts. The use of HTA for game design so far is limited. Applications have focused rather on the use of CTA to create SGs scenarios and articulate the knowledge to guide the players' learning path [46, 38].

3. Transdisciplinary Serious Game Design Approach

Transdisciplinary practice (i.e., transdisciplinary learning and transdisciplinary research) involves different actors (academic and non-academic) to co-produce innovative knowledge [47]. Depending on the approach selected to involve all relevant actors in the knowledge integration, we can distinguish between *consulting* and *participatory* transdisciplinarity [48]. Consulting transdisciplinarity is achieved when non-academic stakeholders are involved through responding and reacting to research conducted by the academic partners (e.g., surveys or experiments with subject matter experts), while participatory transdisciplinarity is achieved when all stakeholders are equally involvement in the full research and knowledge production cycle [48].

The importance of collaboration with domain experts has been often highlighted in relation to serious game design [49, 50, 51]. Literature on SG design [52] identifies four types of involvement of stakeholders in the game design process: (i) *users* (e.g., to refine engagement), (ii) *testers*, (iii) *informants* or (iv) *co-designers*. The *user* and *tester* are consolidated roles in most design fields, including SG design regardless of the transdisciplinary nature of the intervention. The *informant* role is similar to the interpretation of the *consulting role* in transdisciplinarity science, where the stakeholders support the process through their expertise, answering to specific questions. However, *co-designer* in this view is associated with the concept in which stakeholders have to acquire game design skills to engage equally with game designers, which is often very demanding and hard to achieve in practice. This interpretation appears limiting with respect to the roles that stakeholders could have into the SG design process. In fact, we argue that following the concept of *participatory* transdisciplinarity, stakeholders can contribute through their expertise and perspective to a broader scientific, societal and practical discourse and, therefore, should be involved in the different SG design and development phases, also in the absence of game design skills.

Stakeholders' contributions will have to be seamlessly integrated with the game designer's knowledge along the design and development process, forming a transdisciplinary team that brings unique expertise and knowledge. Techniques developed in fields such as human-system integration, human-factors engineering (e.g., task analysis) and principles of participatory design (e.g., community-centered design) can facilitate such integration. In fact, they can help create effective and efficient knowledge elicitation and knowledge representation activities, enhancing quantity and quality of knowledge, while reducing the time commitment. This is an important component, as analyses show that to maximize the effectiveness of participatory design of SGs, stakeholders' involvement should be optimized due to their limited time availability [53]. Some uses of such structured approaches are reported in the literature (Section 2.3), but a systematic use of validated techniques and overall guidance on how to include them into SG design frameworks and practices appears to be limited [16, 54].

Following the model-driven SG design framework in [21], the SG design and development phases can be formalized in the creation of a SG *conceptual model*, a SG *design model* and a SG *implementation mo*del. The SG *conceptual model* is defined as a solution and platform independent description of the problem space relevant to the game under development and its purpose [21]. It should describe the objectives, inputs, outputs, content, assumptions, simplifications and models that govern the world simulated in the game, including aspects related to operational or cognitive processes. The *conceptual model* of the SG feeds the creation of a SG *design model* and a SG *implementation model*. The SG design model is a platform-independent (e.g., analog, computerized, mobile) description of the solution, while the SG *implementation model* is the final platform specific solution developed [21].

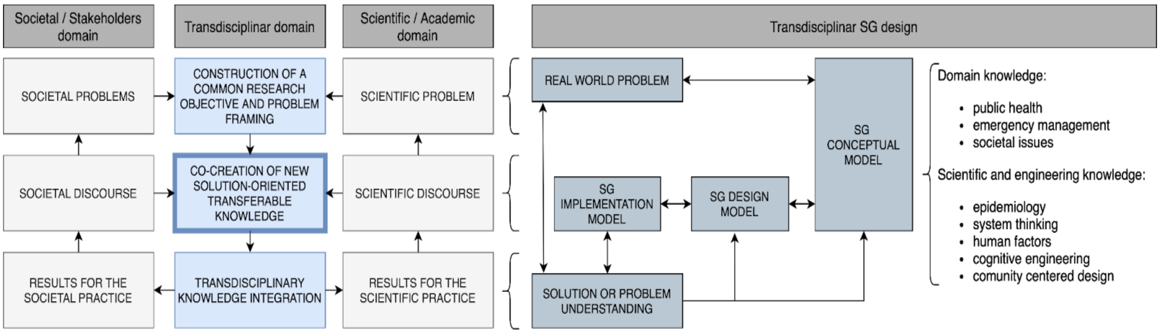

Figure 2. Theoretical framework for transdisciplinarity in serious game design and development.

In order to include an adequate degree of transdisciplinarity and to design targeted evidence-based SGs, the SG *conceptual model* becomes a central step of the design process, which is often overlooked [55]. In fact, the *conceptual model* can act as the bridge between the game artifact, the problem space, the operational context in which the problem needs to be addressed and the scientific theories that might be integrated [55]. Therefore, the SGs design model becomes a focal point of the transdisciplinary design effort, where stakeholders' knowledge is fused with academic knowledge. Both in a consulting and participatory transdisciplinary SG design, stakeholders should be involved as appropriate throughout the design cycle. Depending on the project and circumstances, their specific role might be optimized. For example, a *co-design* role might be more relevant in the SG *conceptual model* creation, as their competences would be better exploited, while in the SG *design model* and SG *implementation modelling* phase they could contribute with a *consultant* role, supporting the game designers and developers.

Figure 2, includes on the right the SG design and development framework [21]. The figure shows how the SG *conceptual model* acts as an integrator of the knowledge and techniques and informs the creation of the SG *design model* and *implementation model*. On the left, the figure shows how the design and development phases map into the transdisciplinary research process model [56]. The transdisciplinary model illustrates that developing solutions for complex societal problems requires establishing links to gaps in existing knowledge and the integration of scientific and societal processes. While the model was created with a focus on research, we could also extend it to education and training for identified knowledge gaps in operational communities (e.g., public health), as it constitutes a complex societal problem. The *conceptual model* is where the transdisciplinary knowledge is collected, structured and integrated. However, stakeholders might play an important role also in the creation of the *design model* and *implementation model*, for example working with the game designers in refining the game elements and mechanics. Finally, the SG will generate new knowledge that will be integrated into the scientific community, stakeholders' communities and society.

4. The C3C Game

4.1 C3C Game Objectives

Command, control, coordination and communication (C3C) are key in crisis and emergency management. Overall guidance on them can be found in a considerable amount of planning instruments at federal, state, regional and local level. However, the complexity of the problem space and the implications of non-technical factors (e.g., political and social) makes it difficult to: (i) navigate between the different plans, (ii) identify the best approaches and (iii) understand which command, control and coordination structure might be more effective and efficient in a specific situation. In fact, the nature of the threat, the contextual situation, the geographical and time extension of the event, the resources available and the regulations in place are only some of the factors that impact such decisions. The recent COVID-19 pandemic exposed several weaknesses with respect to these functions.

The primary objectives of the game are to: (i) provide a safe-to-fail environment to pressure test and critique current plans and concept of operations, (ii) provide an educational and training experience for the decision-makers involved (by allowing them understanding of the perspective of other organizations and by improving their coordination capability and semantic interoperability) and (iii) conduct research to improve efficiency, effectiveness and resilience of the command and control structures during emergencies. Combining training and research objectives in crisis management SGs, appears to have a positive impact on the participation of the target audience of professionals [57]. In the game, several factors related to C3C are monitored and tracked through a specific game board (Figure 3), which includes data gathering areas that take advantage of geometrical features of simple shapes (e.g., a triangle) to easily collect players' beliefs and attitudes [43]. These beliefs can be translated to subjective probabilities or other mathematical quantities in the post-game analysis phase.

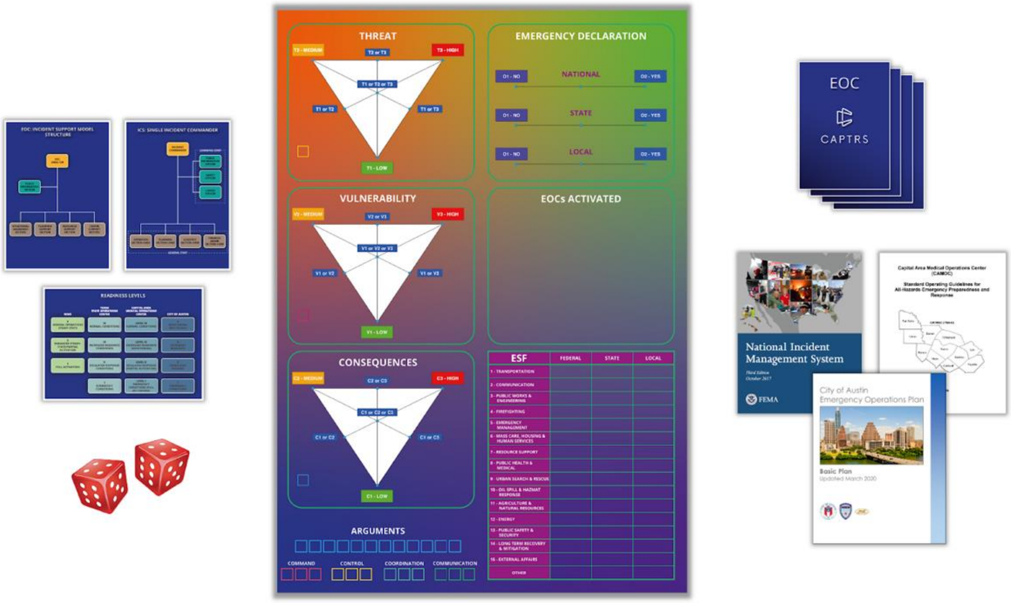

Figure 3. Command, Control, Coordination and Communication (C3C) Game elements: game board (central), flashcards (left), game cards and supporting plans (right) [58].

4.2 Overall gameplay

Players are divided in two teams, an emergency response team (ERT) and a challenge team (CT). The game is run with the support of an exercise control team, composed by the facilitator, note takers and an expert in the specific threat acting as adjudicator and facilitation support. The C3C Game is similar to a traditional Matrix Game wargame [59], in which a confrontation and argument base discussion drives the gameplay. Specifically, the game is organized in five rounds in which an evolving threat situation is presented. In each round players receive a new situational report. At first, all participants (ERT and CT) have time to perform a set of individual assessments. Specifically, they will have to perform the following tasks, each corresponding to a game module (GM):

[GM.1] Situational Assessment, which includes:

(a) a risk assessment;

(b) a resource assessment;

(c) a disaster declaration need assessment;

[GM.2] Decision in relation to:

(a) the declaration of a disaster;

(b) the proper command and control structure to be set up and related staffing;

(c) which Emergency Operation Centers (EOCs) should be activated and the adequate activation level;

(d) definition of the type (e.g., pre-identified physical location, ad-hoc physical location, mobile, virtual or hybrid) and location of the EOCs;

(e) identification of which specific emergency functions service (ESF) should be ensured.

[GM.3] Justifications on why and how the above decisions regarding C3C are considered an adequate response and the evaluation of responses.

After the individual assessments, the facilitator guides the ERT participants in a discussion regarding the individual perspectives and asks to reach a consensus regarding all the above points. Once the ERT team converges towards a consensus, they are requested to identify the arguments in support of their final choices. ERT members can provide up to three arguments per C3C factor under consideration and if specific deviations from official plans are foreseen in their choices, they should be justified in the argumentation. CT needs to define counter-arguments to the ones proposed by the ERT team for the C3C factors and has to identify EFSs not adequately addressed. The adjudicator evaluates the validity of the arguments and counter-arguments, the relative strengths and the originality of the counter-argument, which leads to the assignment of the round score. The originality refers to the possibility that the CT uses one of the weaknesses already identified by the ERT during arguments creation. In fact, the game can be run with different strategies in terms of knowledge provided to the CT. The CT might be an observer during the discussions of the ERT or not, depending on specific exercise training objectives and time allocated to GM.3.

The action implementation success is determined based on the outcome of the throw of two twelve-sided dice. If the number obtained exceeds the success threshold, which is a function of the round score, then the choices are considered implemented successfully. Higher scores in the round will increase the likelihood of successful implementation of the ERT decisions, by lowering the success threshold. The use of dice to simulate that the ERT proposals might not be implemented successfully, allows to account for potential external interventions that are not explicitly modeled in the game. Moreover, the variability of the threshold acts as incentive for the ERT to find plausible and convincing arguments. Future variations might substitute this step with players or adjudication interventions.

4.3 C3C transdisciplinary design approach and methods

To create the C3C Game we followed the transdisciplinary design approach described in Section 3, that allowed us to construct a solid SG conceptual model grounded on the specific operational context. In order to obtain this model that encapsulated and merged all the knowledge from the different domains (e.g., epidemiology, medicine, crisis managers with different roles and responsibilities), we first interacted with the experts to identify the focus of the game. Then we adopted a community-centered design (CCD) approach enhanced with the rigorous structure provided by hierarchical task analysis (HTA), which allowed us to capture the processes characterizing the crisis management for the problem at hand. CCD is a specific human-centered design approach, in which the stakeholder community (i.e., the emergency response decision-makers) and designers co-create the solution to the problem.

CCD engages the community not only to co-design the solution, but also to become part of the design objectives [60]. Moreover, it enhances solution acceptance and the inclusion of the perspectives of vulnerable populations in the target community.

The game design team engaged in a series of structured elicitation sessions, complemented with the desk research of relevant documents and plans regarding C3C factors in pandemic crisis.

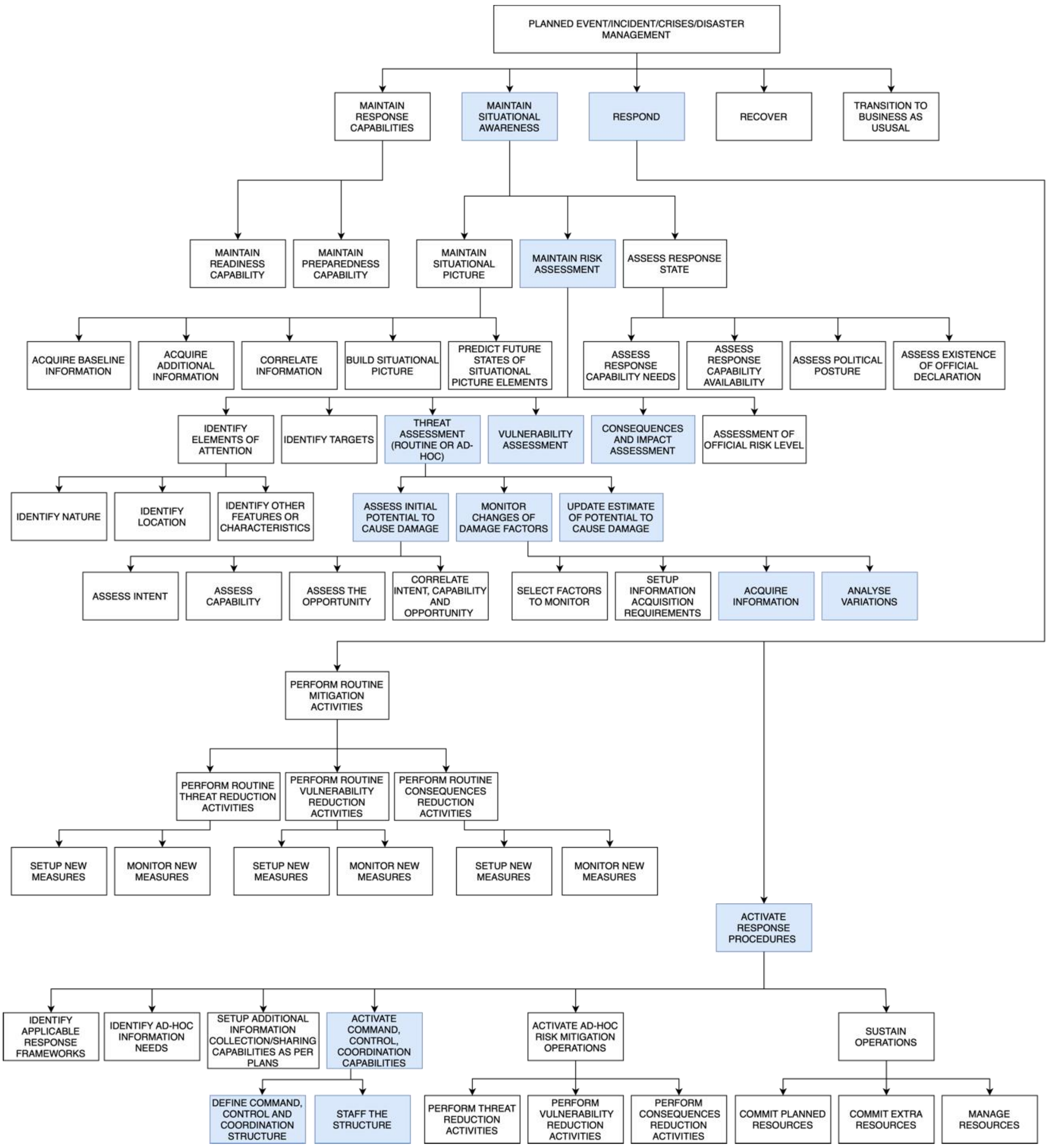

Figure 4. Portion of the C3C Game HTA structure. The structure is simplified for notional reasons and numerical labels are omitted for readability. The light blue subtasks are the ones explicitly included as focus areas in the game.

The resulting knowledge was summarized in a HTA structure (Figure 4) relevant to the focus of the C3C Game and was used to drive design choices for the C3C *design model* (e.g., tasks assigned to the players, mechanics and desired outcomes).

The HTA structure allowed: (i) the identification of key areas that should be the focus of the serious game (e.g., critical areas, error prone activities or under-researched aspects), (ii) the identification of factors' correlation, (iii) visualization of portions of the SG conceptual model (iv) an informed decision on which elements and abstraction level to include in the design. Moreover, the resulting HTA structure supports the game validation activities and might serve as a starting point for conceptual design of new games in the same application domain. For example, the blue elements in Figure 4 are the sub-tasks that have been explicitly included in the gameplay, while the others are not included or performed implicitly by the players. Depending on the specific audience, game objectives and playtime available, each module can be further decomposed following the HTA.

The game has a modular structure in which each task assigned to the players actually corresponds to a specific game module, which is explicitly linked to a portion of the HTA structure and includes specific game elements (Figure 5). The resulting game structure allows to: (i) support the players in their tasks (e.g., flashcards with examples of reference elements of the command-and-control structures that can be instantiated) and (ii) track and record the player assessments and decisions (e.g., portion of the game board). For example, the individual assessments are recorded on an individual game score pad, while the ERT team answers are tracked on the game board (Figure 3). The elements of the individual score pad and the game board are the same. The game board acts as central elements of the gameplay. It is designed to stimulate sharing of perspectives and supporting consensus reaching, while guiding the players through the different assigned tasks (game modules). Both in the individual and group assessments, players need to perform a risk assessment (GM.1.a) and track it through the use of a triangle representing the subjective belief space. This data gathering technique has been used extensively in the previous K2AGs and details can be found in the literature [43]. The risk assessment is decomposed following standard models that are in the HTA.

The risk assessment, in fact, has been divided into threat assessment, vulnerability assessment and impact assessment. As shown in Figure 4, not all the game modules need to link to portions of the HTA at the same level of abstraction. For example, if the training or research objective of the SG is focused on underpinning factors of threat assessment (e.g., nature of the hazard, geographical extension or thresholds that would them make change the assessment), the game might decompose the threat assessment element up to the lowest level of the HTA structure portion describing threat assessment. Instead, the vulnerability assessment and the impact assessment could be described at a more abstract level. After the risk assessment, players perform a resource assessment (GM.1.b), which informs the declaration assessment module (GM.1.c). While in the future this module might be expanded, for this first exercise only a quick unstructured discussion has been performed. This allows us to constrain the time and to capture the relevant factors and parameters to be included in the conceptual model in future developments. In the declaration assessment (GM.2.a), players have to assess their propensity towards declaring a Local Disaster, State Disaster or a Presidential Disaster. The propensity is captured with bipolar scales. During the discussion the players are requested to articulate which are the factors that they take into consideration when assessing the need for a declaration. Finally, they make a decision on whether to declare the disaster or not and they record the decision. Subsequently, players select the C2 structure (GM.2.b), highlighting communication and identifying staffing requirements. Depending on the specific training or research objectives this step could be performed individually and then in the consensus form or directly in the consensus reaching phase, as done in the first pilot exercise. Players will also be requested to decide about the EOCs to activate (GM.2.c and GM.2.d), about which ESFs need to be ensured and at which level (GM.2.e).

Figure 5. Graphical representation of the Hierarchical Task Analysis (HTA) informing the SG models and guiding the creation of players task assignment, game modules and game elements, such as the game board.

4.4 Gameworld design

The players are presented with a simulated situation that could indicate the incept of a public health crisis. Specifically, two passengers (a father and daughter) fall ill with flu-like symptoms on the last few days of a twelve-day cruise in the Caribbean area (Figure 6). When the cruise ship docks in Galveston (Texas) the family is transported to a local hospital, while all other passengers disembark and head to their homes as planned. Each round starts with a brief Situation Update, providing new information on the situation (e.g., number and location of new cases or deaths, time to produce a vaccine and social unrest), on the threat itself and about factors related response efforts (e.g., availability of vaccines). The simulated time interval between Situation Reports is not fixed. In fact, we are simulating a more frequent update at the beginning of the crisis, when the situation is more uncertain and emergency managers and political decision-makers need to understand how to respond. The time interval increases moving forward into the game, to simulate the fact that there is a clearer understanding of the situation, but updates are needed in order to adequately sustain the response efforts and possibly move into the recovery phase.

The scenario is based on the one used in a two-year exercise series of pandemic influenza continuity of operation exercises [61]. The original scenario has been slightly modified to fit the C3C game needs, which included a focus on the City of Austin (Texas, US) and the surrounding region. The modification mainly consists of moving the triggering event (e.g., the disembarkation of the sick travelers and consequent death) to a different geographical area, changing the season of the year to improve consistency with real cruise ship schedules and adding more details regarding the unfolding threat in the different rounds (e.g., epidemiological details). The decision to use a scenario developed for previous exercises was due to the desire to showcase that traditional table-top exercises pre-existing scenarios could be easily integrated into the new game, with little to no modifications.

While the game has been created specifically to improve preparedness for pandemic crisis, the use of the HTA allowed us to align the game to an all-hazard response paradigm, as specified in the US National Incident Management System and National Response Framework [62]. Therefore, it allows us to explore the problem space of C3C at different levels (e.g., local, regional, state, national or international) and to address threats of different nature (e.g., pathogens, climate induced threats, incidents and security issues).

Figure 6. Cruise ship itinerary presented in the scenario (left) and player engaged in the game during the Predictive Intelligence for Pandemic Prevention game-based exercise, which employed the C3C Game (right).

5. A pandemic preparedness game-based exercise

5.1 Exercise Pilot

A pilot exercise was run to assess the C3C Game design and to collect insights on the utility of the proposed extension to the K2AGs to improve decision making when facing a pathogen threat with pandemic potential. Participants to the one-day in-person event included operational and political decision-makers involved in emergency and crisis management at local (city and counties) and regional (e.g., Trauma Service Areas) level in the State of Texas (Figure 5). Demographic details of the players (n = 17) are included in Table 1. One of the exercise participants was not included as an active player, but as part of the exercise control team. In fact, he helped refine and validate the scenario and acted as adjudicator during gameplay.

Table 1. Demographic data of players

Category		Number	%
Age (range)	18-24	0	0%
	25-34	1	5.9%
	35-44	3	17.6%
	45-54	7	41.2%
	55-64	6	35.3%
	65+	0	0%
Gender	Male	10	58.8%
	Female	7	41.2%
	Other	0	0%
	Prefers not to specify	0	0%
Nationality	United States	17	100%
Years experience	Mean	21.0	
	Standard deviation	10.5	

5.2 Results

During gameplay we collected in-game data regarding the individual and team assessments and decisions. This data allowed us to assess the effectiveness and fit for purpose of the game intervention in collecting the intended knowledge and generate the desired confrontation between different players. In addition, we collected pre-game player profiling data and post-game data (i.e., Game Experience Questionnaire - GEQ [63], verbal feedback and written feedback). The post-game data shows that the game was overall positively perceived by the participants. GEQ results (Figure 7) show how participants felt content during gameplay (58.8%), were interested in the game's story (94.1%), were fully occupied with the game (82.4%) and perceived it as a rich (82.4%) and enjoyable experience (94.1%). Moreover, most of the participants appreciated the aesthetic dimension of the game (76.5%). Most participants, did not express negative feelings such as boredom, irritation, annoyance or frustration. Many participants felt deeply concentrated (58.8%), however, further attention should be devoted to understanding the reasons why some participants did not (e.g., length of the exercise) and the potential impacts on the exercise objectives. While several participants (52.9%) reported to feel challenged, others felt only moderately (35.3%) or not challenged (11.7%). This aspect should be further investigated to understand if it might be mainly correlated to the scenario or to the game mechanics. Finally, most players reported that they felt able to explore things in the game (76.5%). From the written general feedback (Figure 8) it appears that players understood well the purpose of the game (70.6%) and considered the topics explored as operationally very relevant (94.1%). Most players considered the game very realistic (70.6%).

Currently no agreed evaluation framework and standards exists to conduct formative evaluation of transdisciplinary research [64]. However, when applying the heuristics proposed in [64] to capture effects of transdisciplinary science the pilot showed positive results both in relation to *first-order effects* and *second-order effects*. *First-order effects* are "direct effects within the duration and the spatial scope of the […] project" [64], while *second-order* ones are "effects beyond the project but within the close temporal or spatial context of the project" [64]. For example, players stated how the game provided an educational and training component (76.5%), as well as an awareness improvement (82.3%). Verbal feedback highlighted how the game allowed them to understand perspectives of other organizations, improving their coordination capability and semantic interoperability. For example, a political decision-maker explained how they are part of the emergency management process, but do not receive formal training. Therefore, the game allowed them to familiarize with procedures, approaches, responsibilities and meaning of different terms. Finally, most of the participants reported that they considered the future inclusion of game-based exercises in their organizations very useful (88.2%). This is considered an important outcome as 82.3% of the players participate regularly into different kinds of exercises, but only 23.5% had been previously exposed to game-based exercises. Moreover, requests have been received regarding the possibility of including the C3C Game into formal training programs. *Third-order effects*, which "are changes beyond the temporal or spatial context of the project in the entire field of action or problem" [64], were not considered, as they are beyond the limited geographical and temporal scale of the pilot.

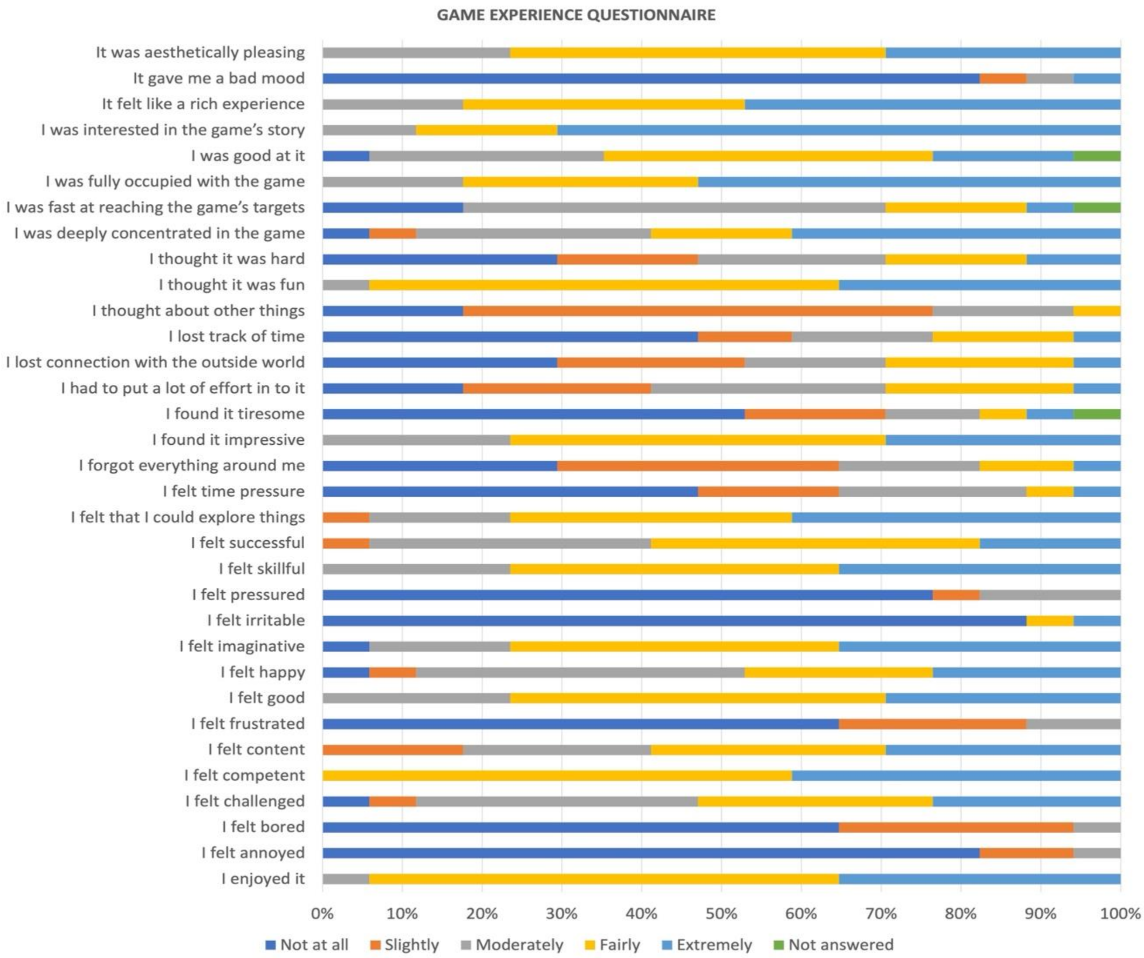

Figure 7. Game Experience Questionnaire (GEQ) results for the first pilot [57]

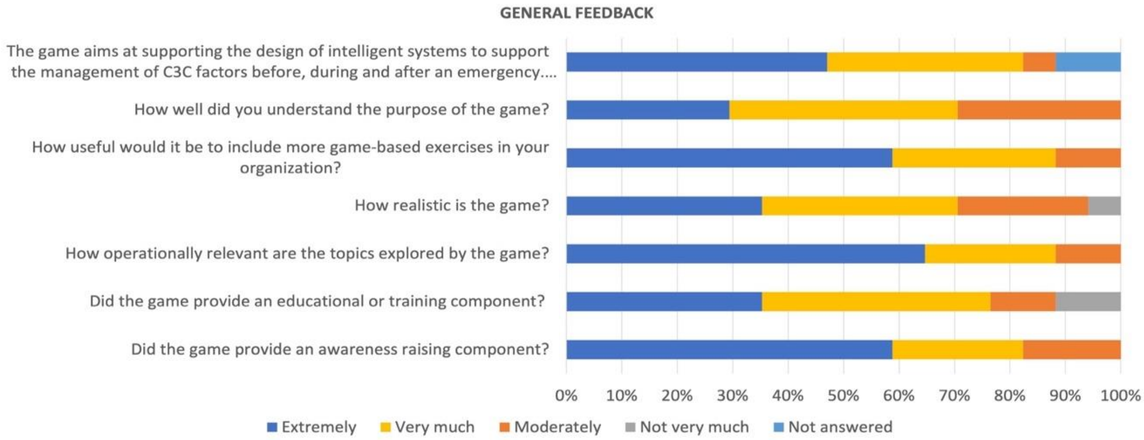

Figure 8. Participants' written feedback answers for the first pilot [57]

5.3 Discussion

The pilot results show that the proposed design approach allowed the co-creation of a game capable of capturing the complexity of the C3C related tasks and transforming them into a simplified model to be used into a game session, while preserving the realism. This is an important aspect, highlighting how the framework and methods applied allowed the extrapolation of the key operational concepts, condensing them to a set of elements that were presented to the players in a highly abstracted way. The abstraction did seem appropriate for the intervention and able to generate the desired gameplay and interactions between the experts in the game session.

With respect to the intended impact of the intervention, the analysis shows positive results in its ability to promote the research and learning objectives. Furthermore, as in overall transdisciplinary design practice [14], the act of co-creation itself acted as mediator (or provocateur) that appears to have the ability to generate insightful knowledge regarding the problem at hand beyond the main design output. In the C3C Game case, this is represented by the resulting HTA, which is a useful by-product that could be used in several other design activities, such as the creation of decision-support systems for C3C or as a starting point for the design or amendment of actual response plans.

With respect to the C3C Game we will continue the development activities, as well as the validation activities to ensure the flexibility to scale across geographical areas (when the threat scenario calls for a large-scale response) and the ability to quickly change threat type without the need for specific changes to the game structure. Moreover, future research will explore the ability to quickly adapt the game to be employed in countries that might have different response paradigms and structures. While on one hand this will allow to refine the C3C Game, on the other it will serve as a use-case to further refine the methods for transdisciplinary design of SGs. For example, we will explore the usefulness of integrating HTA and potentially other human factors approaches into SGs design to identify areas of non-academic knowledge and practice that are transferable between different emergency and crisis management domains (e.g., a pandemic crisis or a natural disaster). It is expected that this would support the design of SGs for crisis management based on generalizable models, which can be finetuned based on the specific project or intervention needs.

With the growing interest towards SGs to address complex socio-technical challenges, attention should be paid to further understanding the implications of integrating transdisciplinary in the SG design process itself. This is a wider challenge in the design discipline, where we still observe a lack of standards, norms, reference methods and agreed approaches to transdisciplinary design lifecycles [15]. As theoretical and practical approaches evolve in the overall design discipline, the SG design field should investigate the implications of the advancements on its own established approaches. Specifically, further research should be performed in identifying high-quality design methods that support and facilitate the co-creation of SGs. Moreover, it should be investigated how these new design methods complement existing SGs design frameworks. The work introduced in this paper is not in contraposition to existing SG design frameworks (e.g., [16,17,19]). Rather it enriches them by focusing on the two main characteristics of transdisciplinary practice (i.e., co-creation and integrated knowledge) and provides a practical example on how to account for them in SGs design. Therefore, it could be interpreted as a building block of a wider guideline and theorization of transdisciplinary practice for SGs. Future work should establish formal links with the overall SGs design approaches.

6. Conclusions

Many socio-technical complex issues require transdisciplinary interventions to address the problem, making sure that all the required knowledge and perspectives are correctly integrated and articulated. In this paper we introduced a theoretical framework to include transdisciplinary principles into the design and development of serious games looking at socially relevant and complex problems, such as crisis management. We showcased how we applied such a framework to guide the creation of the C3C Game, which aims at improving decision making related to command, control, coordination and communication during a crisis. We piloted the game using a public health related scenario with positive results, supporting the idea that the game conceptual model can act as means through which we attain the desired degree of transdisciplinarity. The SG conceptual model becomes the mediator through which the different disciplines' perspectives and knowledge are fused in a coherent picture, using different methods, both new or borrowed by other fields (e.g., design thinking or human factors).

With a strong emphasis on the advancements regarding transdisciplinarity in the design research field, our future work will continue investigating both the theoretical aspects and practical implications of the integration of transdisciplinary principles in serious game design and development. Specific attention will be dedicated to the needed changes in the current SGs evaluation approaches.

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