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Serious games as research instruments – Do's and don'ts from a cross-case-analysis in transportation

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Serious games as research instruments are seen as a special type of participatory modelling, allowing a researcher to observe the behaviour and decisions taken by players. Yet, games have their own dynamics and come with certain challenges when used as a research instrument. This article reports on specific challenges in using games as research instruments in the domain of transportation. Therefore, three digital games from the transportation sub-systems freight transport, airport management and public transport are presented. The cases are analysed according to the challenges faced during the phases of requirements analysis, design, implementation, usage as research instrument, and evaluation. Based on this cross-case analysis of the research games, Do's and Don'ts as well as practical recommendations are derived to support researchers and practitioners in applying serious games as research instruments in transportation. The new ReDIRE-framework to analyse serious games for research purposes is presented for this aim. Design guidelines resulting from our contribution can be helpful for game designers and researchers alike.

Keywords: *complex systems, cross-case analysis, research instrument, serious games, transportation.*

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1. Introduction

1.1 Serious games for complex transportation systems

The domain of transportation faces a number of challenges, especially as it shows characteristics of complex systems. Complex systems are described as systems "in which there are multiple interactions between many different elements of the system" (Ridolfi et al., 2012, p. 39). Due to this nature, disruptive events in transportation can have a significant impact on safety and operative procedures (Svensson, 2000), meaning that one event, for example a delay in a container terminal, can have severe ripple effects on other nodes in the system. Transportation also faces an increasing number of social as well as technological challenges. So, the design and analysis of complex systems is difficult as of the number of interdependent elements.

Transportation research uses a broad spectrum of methods and applies a toolbox of different methods, measures and instruments. Simulation and modelling are frequently used methods of transportation research (Brandenburger et al., 2019; Neumann et al., 2019). As the transportation system is rapidly transforming, research in this domain is challenged to test and assess new intelligent transportation systems in realistic and complex simulation environments (Richter et al., 2020). Yet, as the transportation system is a complex socio-technical system, traffic simulations and modelling approaches must be enriched by a human-centred perspective that brings (choice) behaviour and underlying processes to transportation research (Ottens et al., 2006; Wilson et al., 2007). Serious games fulfil this criterion as they make it possible to analyse human-centred processes in a safe research environment and to also support systems design.

According to Abt (1970), serious games are games with more than just an entertainment purpose. In serious games, players take on different **roles** (Klabbers, 2006) and a previously defined **goal** must be achieved on the basis of a balance between competition and compromises in conflict-laden scenarios (Sauvé et al., 2007). Players must make **decisions** within limited time and with limited **resources** (Klabbers, 2006; Sauvé et al., 2007). A certain set of **rules** must be considered (Schwägele, 2015), as well as having a focus on human behaviour. To focus on this aspect, reality is abstracted, because the more complex and detailed the model underlying the serious game is, the more complex and less transparent it becomes in itself (Schwägele, 2015)[6].

In general, serious games represent simplified models of a real system (Kriz, 2003). This simplification is needed to analyse human behaviour in an interactive, but at the same time safe environment (Kriz, 2003). The perceived safety of a game environment enables researchers to observe players' behaviour and decision-making processes (Van den Hoogen et al., 2012). Game elements, such as events and action sequences, can be pre-scripted and offer a quasi-experimental environment. In contrast to simulations, serious games are less context-specific but make use of fantastical contexts, elements and characters (Charsky, 2010) with the aim to motivate players to explore the gaming environment. Lukosch et al. (2018, p. 280) have stated that games are "a powerful approach towards the understanding of highly integrated, large-scale systems with many actors dealing with deep uncertainties." As Hense and Kriz (2008) pointed out, serious games are 'powerful tools' for simulating and analysing dynamic processes. Furthermore, attributes of serious games like immediate feedback, immersive and experimental environments, and automated data collection make digital games attractive as research tools (Noy et al., 2006). Yet, games also come with their own dynamic which might include some unpredictable events during gameplay. "However, there is a strong potential for simulation games to be research instruments since games produce an abundance of data related to user experience, decision-making, human behavior and skills" (Lukosch et al., 2015, p. 2). As in the transportation domain collaborative and competitive interdependencies between actors are very high, the planning of operations and the

[6] These characteristics and elements as part of the definition of serious games have been mentioned and summarized in Freese (2019).

analysis of collaboration and decision-making is uncertain, complex and challenging (Lukosch et al., 2015), which in turn requires interactive research methods like serious games.

Due to the named benefits of games, the transportation domain already makes use of games as a tool for informing citizens about transport systems (Brannolte et al., 2004), initiating discussions among stakeholders (Guimarães et al., 2014; Rosetti et al., 2013), specifying user requirements (Gabrielli et al., 2013), and for policy exercises (Schiefelbusch, 2005). Adding on this, the potential of serious games for studying user perception, choice and behaviour is exploited in behavioural modelling tools in different transportation subfields, like road safety (Ariffin et al., 2010), driver-assistance systems and autonomous driving (Ebnali et al., 2019; Gonçalves et al., 2014), and microscopic traffic modelling (Biurrun-Quel et al., 2017; Rosetti et al., 2013).

1.2 Research gap and scope

Numerous design principles for the development of serious games and scientific discovery games exist (e.g., Cooper et al., 2010; Duke and Geurts, 2004; Harteveld et al., 2010). One approach towards using games in research is made by Aarseth (2003). Yet, he approaches games from an aesthetics point of view mainly, which puts his work into the area of games studies (thus, the study of games itself) rather than adding knowledge to the use of games as research instruments. Grogan and Meijer (2017) propose games as instruments in engineering systems research. When approaching transportation as a complex system, we can apply their model to games for transportation research. They provide a comprehensive overview of disciplines that inform the science of games as research means in systems engineering, and discuss their role along the axes of analytical and design science. Their work does not discuss practical implications for researchers who aim to apply games as research instruments. Roungas et al. (2018) conceptualise games as modelling method for complex systems. Their work identifies limitations of the field, and proposes solutions to address those. Yet, the study addresses serious games in very general terms, not necessarily limiting the study to games as research tools.

To conclude, design principles for serious games as research tools in transportation have been rather underexplored and "a well-grounded method in game research is still lacking" (Lukosch et al., 2015, p. 10). In addition to this, when using an experimental research design, traditional models for evaluating games (e.g., Hainey and Connolly, 2010; Yusoff, 2010) have to be extended to deal with the restrictions of usage as a research tool.

To add to the body of knowledge on serious games as discussed above, the main contribution of this paper is on using serious games as research instruments to analyse complex systems in the transportation domain. However, Lukosch et al. (2018, p. 284) address one of the limitations of the field of serious gaming research, as "no best practices or established frameworks for the use of games as research tool exist yet."

With our work, we aim at contributing to the further development and foundation of serious games as research instrument and to provide researchers and practitioners in different transportation domains that strive for an extension of their methodological toolbox. Following the approach of Duke and Geurts (2004) for designing and using policy exercises, our contribution aims to describe the process of developing and using games as research instruments and derive recommendations. Especially in the transportation system, we recognized that the design and development process of serious games is challenging due to the characteristics of a complex system on the one hand, and due to the numerous challenges that this domain faces on the other. Based on our experiences, existing serious game design approaches often do not consider today's complexity nor give recommendations on what specific decisions need to be made when serious games are used for research in the transportation domain. Those significant practical problems formed a related research question that the present paper addresses as:

- What criteria should be considered for the design, development and use of serious games as transportation research instruments?

By answering this research question, the article aims to identify challenges in the process of the development and the application of serious games to the field of transportation. Furthermore, the article's objectives are to present Do's and Don'ts based on the assessment of three cases and to derive recommendations for researchers and practitioners from different transportation domains.

2. Methodological approach

In our publication, we present and discuss a 3-step methodological approach. First, we focus on a cross-case-analysis. Therefore, three serious games from different transportation sub-domains are analysed. We have chosen these games because of their application in the same research domain (transportation) and a similar project development size. To compare the different games, we briefly introduce them along their basic elements. Our description is based on the Mechanics, Dynamics and Aesthetics approach (MDA) defined by Hunicke et al. (2004). In addition, we discuss how we designed and used these games as research instruments. Based on the amended MDA framework, it is possible to compare the game structure of the three serious games with each other. Secondly, a comparison of existing game design approaches is presented that concludes in the new ReDIRE framework for the analysis of serious games as research instruments. This framework analyses serious games regarding the key steps of design, development, and evaluation. The three example games are analysed according to this framework, including the challenges faced during the phases of requirements analysis, design, implementation, usage of games as research instrument and evaluation. Thirdly, based on the comparative analysis of the three research games, Do's and Don'ts as well as practical recommendations are derived to support researchers and practitioners in developing serious games as research instruments in transportation. The main target groups of this case study analysis are transportation engineers and practitioners from different transportation domains planning to incorporate serious games as transportation research instruments.

3. Description of three serious games in transportation

For a better understanding and comparison of the serious games, we use the MDA approach (Hunicke et al., 2004). This model represents a relation between game design decisions expressed as **M**echanics, **D**ynamics, and **A**esthetics, and the respective player experiences of rules, system and 'fun'. The analysis that is based on MDA is used in an iterative manner during the game development process (Hunicke et al., 2004). Yet, it is also possible to apply the MDA approach to an already existing game. Then, a reverse engineering approach is used where the experienced aesthetics are traced back to the mechanics. By breaking the game down to such design elements, it becomes possible to compare games with each other. This is how we applied the MDA approach to the three cases represented below.

In the next three sub-sections, three serious games from the transportation sub-systems freight transport, airport management and public transport will be discussed by shortly presenting the aim, the development process and the use as research instrument of the games based on the MDA approach. It should be emphasized that the games were not evaluated as an artefact but regarding to their capacity and suitability as a research instrument. All of the three games were thus evaluated by the researchers and not by the users.

3.1 Yard Crane Scheduler – A serious game for freight transportation

The particular development of the Yard Crane Scheduler (YCS) game has been motivated by the increased need for transportation of goods that has seen a constant growth during the last decades due to globalized markets and competition (Mačiulis et al., 2009). Planning and managing the stream of freight is a complex task, and a serious game can be used to study skills needed to handle interdependent assets in freight transportation.

Games as research instruments in freight transportation. Serious games are an accepted tool in exploring freight transportation aspects as shown in the works of several authors (Kourounioti et al., 2018; Kurapati et al., 2015; Kurapati et al., 2017; Meijer, 2009). While Meijer (2009) addresses a problem on a strategic level, Kurapati et al. (2015) suggest the use of short games on an operational level in transportation. Kurapati et al. (2017) as well as Kourounioti et al. (2018) discuss the use of games for the governance of the transport system as a whole, and awareness for synchromodal transport solutions in particular. The above studies have shown that serious games are valuable research instruments on different levels in freight transportation, as they represent controllable, safe environments that allow both for experimentation and for observation of behaviour and decision-making processes.

Aim of the game. For the development of the YCS game, a game development process had been initiated in order to design a well-balanced Microgame according to the Triadic Game Design approach (Harteveld, 2011). This approach proposes to design a game with regard to the real or reference system underlying the game model, its goal or meaning, and the play element(s) of a game. A container terminal as reference system was chosen for YCS. Such terminal is usually composed out of three operational areas – seaside operations, storage operations, and landside operations. As analysed by Kurapati et al. (2015), four major divisions of planning operations within a container terminal can be identified, including berth planning, yard planning, vessel planning and resource allocation. The play aspect of YCS is mainly based on the challenge a player faces when wanting to master the game and get as high a score as possible. The purpose or aim of the game is twofold. On the one hand, the game has been designed in order to train the situational awareness of planners in container terminals. Secondly, and for this article more importantly, the game was designed and used for research purposes. Together with additional instruments, such as a questionnaire, a personality test, and a multitasking test, the relation between distinct personal characteristics and skills related to interdependent planning was explored (see for more details Lukosch et al., 2016).

Description of the game. Following the MDA framework, the main **M**echanics of the YCS game are to manage the yard and align various planning and resource allocation activities in the container terminal. The cognitive load is quite high because of the different tasks that have to be carried out simultaneously. The game mechanics are relatively easy to learn as they only include a limited set of actions, yet mastering the game and getting a high score is hard to accomplish. Players often do not want to stop playing, but want to try and improve themselves. The game is based on two main **D**ynamics – planning and distribution of containers in the yard, and allocation of resources to ensure maximum utilization. If these two challenges are solved, the time the ship needs to spend at the terminal will decrease, which is a major key performance indicator for a real terminal as it determines customer satisfaction (Kurapati et al., 2014). With regard to the **A**esthetics, the player is challenged by the need of synchronous handling of resources in a visually simplified version of a container terminal from a bird's eye view. Assets that are represented are the yard and quay cranes that have to be positioned, as well as the container that have to be allocated in the yard and on the arriving vessels. All vital assets and operations are visualized in the game interface, as can be seen in Figure 1. The game provides an overview of key performance indicators reached at the end of a level completed as feedback and motivation for the player to improve the own performance.

Evaluation of the game as research instrument. Used as a research instrument, the YCS game showed its potential especially as it is relatively easy to play, but hard to master. The game was evaluated in a combination with additional tools such as a personality and multitasking tests, which made it a valuable exercise for research. With the comprehensive test set-up, the researchers were able to gather data that relate in-game performance and player characteristics such as game-play experience, gender, personality traits, and multitasking performance to the challenges of interdependent planning tasks in a container terminal. The main findings can be found in Lukosch et al. (2016).

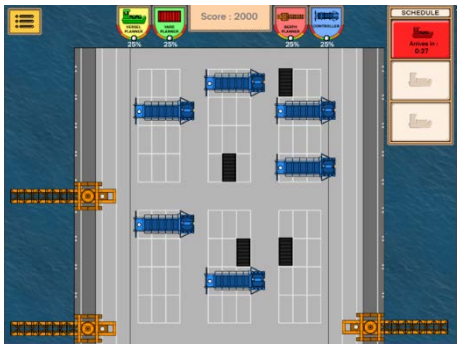

Figure 1. Screenshot of the YCS game

3.2 D-CITE – A serious game for airport management

An airport is a complex system where many actors are involved in. They all must work together to guarantee an efficient and safe air traffic system. Because of different and competitive goals, this is not always easy to realize. All these stakeholders must continuously work on the optimization of processes and their way of working with each other might have an influence on the efficiency of the air traffic system (Papenfuß et al., 2015). One possibility to foster the collaboration is to offer approaches for creating a better understanding of each other.

Games as research instruments in airport management. A few examples of paper-based games (e.g., Skyboard; Maij and Jansen, 2013), digital serious games (e.g., TeamTris; van der Pal and Justen, 2011), and gamified approaches (Mantouka et al., 2019) exist that address airport management-related topics. However, serious games used as research instruments are still underrepresented, yet of crucial relevance in this safety critical domain. Serious games provide a safe environment to analyse human behaviour and related processes that cannot be analysed in a real working environment due to safety or ethical reasons. With the aim to analyse collaborative decision-making processes in airport management, the research instrument '**D**ecisions based on **C**ollaborative **I**nteractions in **TE**ams' (D-CITE; Freese et al., 2015) has been developed.

Aim of the game. By using D-CITE it is possible to analyse human behaviour, but also influence factors on the airport managers' decision-making processes. For that reason, D-CITE includes individual interests of each stakeholder and considers them in the decision-making process at airports.

Description of the game. D-CITE is a computer-based multiplayer game (Freese et al., 2015), which is playable for four to five players. They assume the role of either one of the two airlines, an airport authority or a ground-handler. The basic gameplay of D-CITE consists of five rounds. The goal of all players within D-CITE is to optimize the business of an airport. Therefore, they must reach a high numerical team score. To do so, all players have to collect financial resources (money), but, at the same time, they are also responsible for passenger satisfaction and must gain coins for it. If players share useful information, they also get more points. Each player has only limited knowledge about the systems of the other players. To get more knowledge and a better understanding of the interdependencies, they must communicate, interact and collaborate with each other (Freese and Drees, 2015; Freese et al., 2015). Furthermore, all players have the separate task of attaining the highest possible economic success for their own little business (Freese and Drees, 2015; Freese et al., 2015). Two screenshots of D-CITE can be found in Figure 2.

Based on the MDA analysis, the main **M**echanics of D-CITE are: players (depending on the specific role) are able to plan aircrafts, check the passenger handling as well as truck and bus movements. They can work on these tasks within a certain number of rounds. The number of complexity increases with the number of rounds. The mentioned mechanics and the goal of the game support the dynamics. In this case, the **D**ynamics are (strategic) planning and time pressure which lead to a number of challenges within the game. The players have to make decision within a certain time period. Furthermore, they have to consider critical events (e.g., bird strike; Metz et al., 2016). Based

on these challenges, players have to find a good balance of a cooperative or competitive business. Regarding the **A**esthetics, challenges are created by time pressure, the analysis of critical events as well as an increasing complexity and change between competition and cooperation.

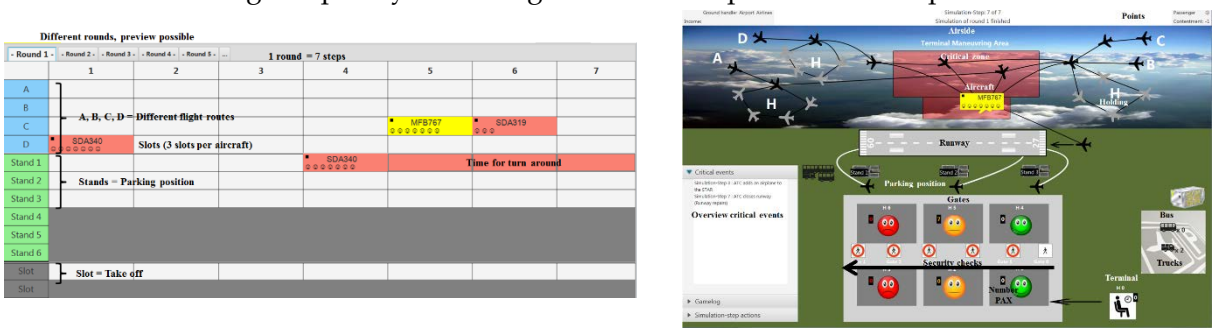

Figure 2. Screenshot of D-CITE (Freese et al., 2015)

Evaluation of the game as research instrument. D-CITE was evaluated based on studies with school and university students as well as with airport managers. Therefore, a classical experimental approach using different conditions as well as repeated measurements has been used. More details about the evaluation of D-CITE as a transportation research instrument can be found in Freese and Drees (2015), Freese and Jipp (2016) and Freese et al. (2016).

3.3 B.u.S. – A serious game for public transport

The public transport sector is facing significant challenges due to technological trends like digitalization as well as social changes, changing work styles and the sharing economy (Marsden et al., 2018). Yet, new sustainable mobility solutions, such as mobility-as-a-service are often insufficiently introduced to the prospective users and factors that affect the adaptation process have been rarely examined (König et al., 2017).

Games as research instruments in public transport. Research games provide a basis to study transformation processes and might also contribute to shape the direction of these changes. Games in the public transport domain are mainly used to study decision-making processes (Bekebrede, 2010; Duffhues et al., 2014), to enhance players' knowledge about mobility behaviour and transport systems (Brannolte et al., 2004; Yusoff, 2010) or as persuasive games to change players' mobility behaviour (Gabrielli et al., 2013; MUV, 2018).

Aim of the game. The objective behind B.u.S. (German: '**B**ürger **u**nterrichten durch **S**piele', English: "Teaching citizens with games") is to support knowledge acquisition and comprehension about the operating concept of a demand responsive transport systems (DRT) since the acceptance and usage intention of transport innovations depend on the prospective users' understanding of the service concept and how to use the service (Laws et al., 2009). Specifically, three types of knowledge according to Rogers (2003) are intended to be increased by playing the game: awareness-knowledge, how-to-knowledge and principles-knowledge. Furthermore, B.u.S. aims to point out differences between the service concepts of DRT services and fixed scheduled public busses. Another objective is to improve players' appraisal of DRT systems by demonstrating the benefits to the user and thus improving perceived usefulness of the new public bus concept (König et al., 2017).

Description of the game. Within the game B.u.S., players assume the role of a public traffic planner of a virtual city to plan and operate a DRT system that satisfies the mobility needs of the local residents on the one hand and meets the goal of an efficient and environmental friendly operation on the other hand (see Fig. 3). The players' task is to collect travellers at bus stops and to combine routes in order to handle the travellers' demand for fast and direct transport on the one hand and to avoid empty runs on the other hand (König et al., 2019). The inclusion of different actors in the

system honours the complex character of the transport systems and the interactions between many different elements of the system.

Based on the MDA approach, the main **M**echanics are sending the bus, collecting the travellers and dropping passengers off. The difficulty of the quests increases in a level-based approach. The mechanics create the **D**ynamics of different game elements like the passengers, the map and route and thus create time pressure and strategic planning. Especially these dynamics create the **A**esthetic of challenge. By observing the DRT behaviour, the aesthetic of discovery is created. The increasing difficulty aims to bring the player into the flow state and causes the aesthetic of submission. A special focus is set on the aesthetic of discovery by using the experimental game approach by de Freitas and Neumann (2010). Accordingly, players are encouraged to actively deal with the bus system and in this way experience system characteristics and constraints, like the spatial and timely flexibility of the operational concept.

Figure 3. Screenshot of a game situation in level 5 of the B.u.S. game

Evaluation of the game as research instrument. The serious game B.u.S. was evaluated based on a classical experimental design using a pre- and a post-test and a control group design (Hainey and Connolly, 2010). The evaluation study was performed in a secondary-school setting with 71 pupils in a rural area with DRT operation. The study participants were randomly assigned to two groups: 1) the experimental group that played the game for 15 minutes and reflected on the game for five minutes and 2) the control group that did an online research concerning DRT systems for 20 minutes. Both groups completed questionnaires before and after the experimental session to assess changes in knowledge, attitudes and behavioural intention to use the DRT. More information on the evaluation study and the findings can be found in König et al. (2019).

As can be seen, the three games address different challenges of complex transportation systems, and rely on different dynamics, mechanics and aesthetics. Yet, all three aim at supporting actors in getting a better understanding of the complex system, eventually leading to being better prepared to handle the system.

4. Analysis of the three serious games as research instruments and related challenges

The article's objectives are to present Do's and Don'ts based on the assessment of the three cases and to derive recommendations for researchers and practitioners. Therefore, all three serious games are analysed according to the challenges they faced during the design and development process and the use as research instruments, along with an explanation of how these challenges have been addressed. In order to structurally compare the challenges, we developed a framework to analyse game design approaches when games are used for research purposes.

4.1 ReDIRE – Framework to analyse game design approaches

There are many traditional and modern approaches with regard to the design and development of serious games that can also be used to analyse existing games. Freese and Lukosch (2019) compared existing game design approaches with each other. They found out that all of them consider complexity, but in different ways. Most approaches have a different understanding of what complexity is about. In addition to this, these approaches see complexity on different levels – from individual to organizational aspects. Furthermore, most of the existing game design approaches mainly focus on the design and development of paper-based games. Therefore, they consider different phases of development but they do not provide specific recommendations on which design decisions need to be made, especially when it comes to the development of digital serious games. Furthermore, existing game design approaches often neglect the specific requirements for designing a game for research purposes. To the best of our knowledge only few empirical studies evaluated the effectiveness of serious games for research purposes (Donchin, 1995; Kurapati, 2017; Noy et al., 2006).

The most well-known and often cited serious game design and development approaches can be found in Figure 4. This figure shows which aspect of the game design process the respective approaches mainly focus on. All of the approaches summarized in the figure address certain game design-related elements from different perspectives. For example, Duke (1974) and Meijer (2009) are based in the policy domain. Some of them cover multiple elements of the game development process, but none covers the whole process of the five steps we defined. Based on the results of Freese and Lukosch (2019) and the analysis of the three cases, we were able to develop the ReDIRE framework (based on **Re**quirement analysis, **D**esign concept, **I**mplementation, **R**esearch framework, **E**valuation, see Fig. 4) that can be used to analyse, compare and validate games.

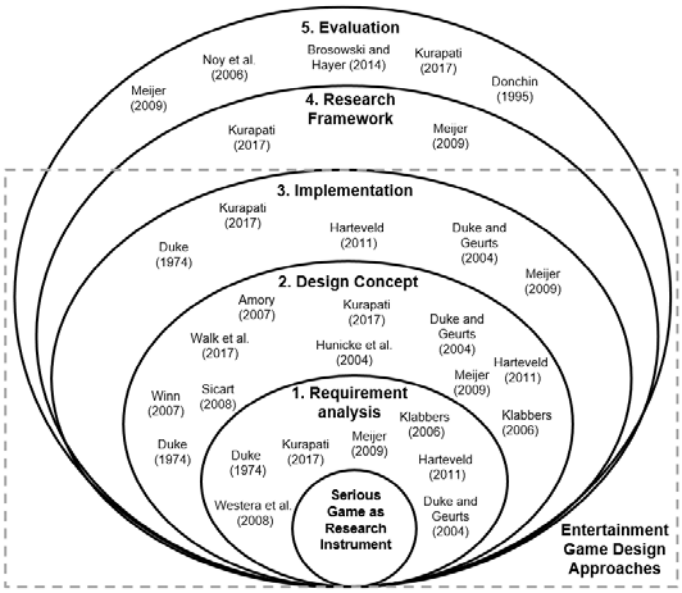

Figure 4. ReDIRE – Framework to analyse serious games for research purposes

The core of Figure 4 represents the aim of designing a serious game for research purposes and the ReDIRE framework clusters existing game design approaches into five categories. These categories were identified when carefully reviewing the referenced game design approaches (see also Freese and Lukosch, 2019). We want to highlight that also existing entertainment game design approaches can be used for the development of a serious game, at least up to a certain level that. This is visualized by the dashed line in Figure 4.

We shortly explain every category of the ReDIRE framework as shown in Figure 4 that already highlight some generic challenges that researchers face when using games as research instrument.

We defined the five categories based on a systematic review of the references included. While not all studies focus on all categories, these are the steps that all of them acknowledge as being vital for serious games development and usage in a research context.

1. The category '**requirement analysis**' is a first main step for the development of a valid serious game. Validity with regard to serious games is defined as the "degree of correspondence between the reference system and the simulated model thereof" (Peters et al., 1998, p. 23). This category includes a critical discussion on whether a serious game might be the right methodological approach for addressing the specific research question. In addition to this, a game developer has to analyse and define a problem that the game should address, define the target group (e.g., Duke, 1974) and consider the resources that are available. When using games for research, the research question is a leading aspect in this phase.
2. The second identified category is called '**design concept**'. In this phase a lot of decisions need to be made. Decisions of this category depend on the outcome of the first phase, especially the research question. To be able to develop an engaging game, game mechanics are needed. Based on Sicart (2008), game mechanics are defined as "methods invoked by agents, designed for interaction with the game state." An engaging game works towards a flow (Csíkszentmihályi, 1990), an enjoyable state in which people have the strong intention to follow up with what they are doing, for which an adequate balance of game mechanics is relevant. Games are simplified models of reality, and the design concept of games for research needs to be based on the right degree of reality (fidelity) of the game (Harteveld, 2011; Lukosch et al., 2019) in order to represent a valid reference to reality.
3. Based on our analysis, we identify the '**implementation**' of a serious game as a third important category for the design and development of a game for research. In particular, conducting playtests is one important aspect of this phase with the aim to debug and polish the game and to check the validity of it as well (e.g., Kurapati, 2017). As a consequence, an invalid game used as a research instrument can lead to 'wrong' research results. Another aspect of this category is to carefully analyse the organizational context of the game, and the role of the game in the general research methodology.
4. Planning the '**research framework**' is the fourth category we identified. This phase contains the consideration of a briefing and debriefing phase. Furthermore, the selection and collection of data is another step that needs to be taken into account. There are behavioural measures, physiological and cognitive test measurements and we also distinguish between quantitative and qualitative data collection. All of them have advantages and disadvantages and the choice for one/some of them depends on the specific research question.
5. As a last step of the design and development of a serious game used as a research instrument we identified the category '**evaluation**'. In this phase, the transfer back to the real system is needed (Kriz, 2003; van der Kooji et al., 2015). The evaluation thereby focusses on the suitability of the serious game as a research instrument and not on the game as an artefact concerning the distinct elements of the game itself. The debriefing phase of a game is part of this category, as it connects the experiences of players and researchers/observers, understood as learning from the game to reality (Crookall, 2014; Kriz, 2010).

Most of the already existing game design approaches can be clustered in the first three categories of the ReDIRE framework. Yet, there are just a few approaches that focus specifically on the use of serious games as research instruments and their evaluation (Brosowski and Hayer, 2014; Kurapati, 2017). Hainey and Connolly (2010) emphasize the lack of empirical evidence and evaluation frameworks in game-based learning. The identified five categories of the new framework are the

basis for further comparison of the specific challenges of three serious games from the transportation domain that were introduced above.

4.2 Cross-Case-Analysis on specific challenges during the design and development process of a serious game and the use as research instrument

The new developed ReDIRE framework already highlights some general challenges when designing, developing and using serious research games. To specify these challenges for researchers and practitioners in different transportation domains, we present and discuss distinct design, development, implementation and evaluation challenges identified for serious games in transportation research. These challenges are the result of a thorough analysis of the development, implementation and evaluation process of the three games, guided by related literature. To guarantee a clear focus of the analysis, we derived challenges described in relevant literature and based on the five main categories of the ReDIRE framework. To illustrate the respective challenge, we provide specific examples of the previously described three serious games.

1. Requirements analysis. Especially the analysis of a concrete problem statement has been identified as main challenge for all three serious games. Defining a concrete problem statement often is difficult to realize due to the nature of complex systems that are characterized by different actors with different goals and priorities, interdependencies and collaborations under uncertainties (de Bruijn and Herder, 2008). Complexity becomes even more important on account of increasing dynamics, more interconnectedness and complex, uncertain problems. The problem which the game should address was challenging to define for all three games due to the complexity of the underlying transportation systems. Defining the target group on the other hand was relatively easy to address for all of the three games. In the requirement phase, the project team of B.u.S. was challenged to decide whether a game, a simulation or a gamification approach would be more suitable as a tool for the concrete research purpose.

Main criteria of the requirements analysis, based on challenges identified for this phase:

- Decide whether a serious game is a valid method to analyse the problem (Sauvé et al., 2007).
- Analyse and define a concrete problem which the game should address (Freese and Lukosch, 2019).
- Think about the target group. For instance, are the problem owners also the players of the game?
- Decide for the number of players (Harteveld and Bekebrede, 2011).
- Handle resources (time, money, quality) for game development (Kuster et al., 2015).

2. Design Concept. The balance between non-game and game realism is an important aspect and was one of the challenges that was important for all three serious games. Since serious games represent a simplified model of reality, the right degree of reality needs to be identified and the game model should be created in a way that it is a valid representation of the real world (Peters et al., 1998). In designing the YCS game, the biggest challenge was to deal with the simplification of reality that is needed to create a meaningful and engaging game experience. The developer of D-CITE faced the same challenge and had to think about questions like: how can we guarantee the right amount of reality and which elements are important enough to become part of the game, which are not?

Another important design aspect is the consideration and balance of game mechanics. Game mechanics are rule-based systems that motivate players to explore and learn (Sicart, 2008). The feedback of the players shows that the game mechanics of YCS are quite challenging. Experienced players, who are more familiar with video games, seem to have an advantage above players without this background. Another topic that is connected to the game mechanics is the balance of the flow of a game. The game should have the right balance between challenging but doable tasks.

This topic was an issue during the development of D-CITE and B.u.S.. The level of difficulty within the game missions was likewise a relevant challenge in the design process because a gaming situation in which players' skills and the challenges of the missions are balanced is an important precondition for achieving a condition of immersion and flow (Csíkszentmihályi, 1988) instead of overload or boredom (Shute, 2011). Choosing the right genre for a serious game is closely tied to its content and goals. This leads to a wide range of genres used in serious games for example adventure games (Energy Cat [FremenCorp, 2016], Sea Hero Quest [Glitchers, 2016]), simulation games (the games analysed in the paper) and many more.

Main criteria for developing a design concept, based on the challenges identified for this phase:

- Decide for the right genre. There are different genres, like action, adventure, strategy, role-playing, puzzle etc. (Ratan and Ritterfeld, 2009).
- Define the perspective of the player(s) in the game: First person vs. Top-down vs. Side-scrolling (Denisova and Cairns, 2015).
- Consider and balance of game mechanics, like role change, competition, time pressure etc. (Sicart, 2008).
- Decide for the right degree of abstraction and identification with the real world, so the game model is a valid representation of the real world (Klein, 1985; Peters et al., 1998).
- Check the modus of the game: Games can be played as single (communication between humans and AI) but also as multiplayer games (communication between humans) (van Rosmalen et al., 2012).
- Define ways to make the game playful, for instance by using narrative elements to increase immersion (Ip, 2011; Qin et al., 2009).
- Balance the flow. The game should not be too difficult, which might lead to frustration or overload, nor too easy, to avoid boredom (Shute, 2011; Swink, 2009).
- Decide for an in-game time concept (real-time strategy vs. round-based) (Juul, 2005).
- Define the way of informing the players about rules: by presenting them at the beginning of the game or let the players explore them?
- Consider human-machine-interaction design aspects, like graphical representation of the game (2D vs. 2.5D vs. 3D).
- Decide whether to design the game together with experts of the specific field grounded on a systematic analysis of the reference system (Lukosch et al., 2015).

3. Implementation. With regard to the implementation of digital games in a real system, we have recognized that the analysis of problems and debugging of those need to be taken into account. This was especially a problem in the development of YCS, as the reality had to be heavily simplified, and of D-CITE because this game was supposed to be a multiplayer game.

Another challenge we identified was the proof of a valid game. Especially for the development of B.u.S., the ecological validity (Brewer, 2000) was a challenge. Since the aim of the game was to enhance knowledge and the willingness to use the bus system in real life, the correspondence of simulated game system and real-world reference system was of uttermost importance in the game design process (Lukosch et al., 2015).

Main criteria for the implementation, based on the challenges identified for this phase:

- Implement first game design concepts with rapid prototyping (e.g., paper-based mock-up) (Lukosch et al., 2015).

- Conduct playtests to guarantee a playable research instrument. Decide for a sufficient number of playtests (Lukosch et al., 2015).
- Debug all the problems and polish the game.
- Check whether the game is internal and external valid. Therefore, checklists exist but you can also consider an iterative procedure where experts can be involved to support you with feedback (Grogan and Meijer, 2017; Gundry and Deterding, 2018; Van den Hoogen et al., 2016).

4. Research framework. To connect the game with the real world, a structured debriefing is needed (Kriz, 2010). In the case of YCS, which was designed as a tool both for learning and research, the researchers experienced a challenge when balancing the learner needs with their own research goals. For university students with a background in supply chain management, the session was designed in a way that was engaging, and meaningful. Yet, the whole session was also scripted to allow for repetition, and comparison of multiple sessions for research purposes. The decision for the right tool to collect the data concerning the effects of the game on knowledge, attitude and willingness to use was difficult for B.u.S. (König et al., 2019). The combination of qualitative and quantitative data as required by Lukosch et al. (2015) for the assessment of the game's effectiveness in reaching the research aims was an important challenge for all three games. For a comprehensive data analysis, the logging of all relevant players' choices and actions is an essential requirement. Another recurring challenge of all games was seen in the consideration of varying conditions of the specific test settings, like the daytime, or the composition of the test group. The collection of data was also an issue during the development and use of D-CITE. Traditional methodological approaches of experimental studies base on the comparison with a control group that is faced with no or another treatment, yet the careful selection of a comparative measure for the control group was a challenging task for D-CITE and B.u.S.. In the development phase of B.u.S., the selection of an appropriate task for the control group was difficult since it should be ecological valid on the one hand, meaning that it can be transferred to the real world as well as comparable to the gaming task of the experimental group on the other. Furthermore, it was challenging for the developers of B.u.S. to decide whether the study participation should be mandatory during a class or voluntary in the leisure time of the pupils (König et al., 2019).

Main criteria of the development process of the research framework, based on the challenges identified for this phase:

- Think about the role of a facilitator during the gameplay and the possible impact of him/her on the gameplay and the study outcomes.
- Work on a good standardized briefing.
- Decide for a suitable study design (quasi-experimental, randomized control trial, pre-test/post-test design, with or without control group etc.) (Connolly et al., 2012).
- Assess the generalisability of the study findings to the target population with respect to the size and representativeness of sample (Connolly et al., 2012).
- Work on a well-structured debriefing that considers emotions, event, experience and everyday life (Bartschat and Schwägele, 2014; Crookall, 1992, 2010).
- Ensure reliable data collection, think about the right measurements to be able to measure qualitative and quantitative data, especially a way to combine different instruments (Lukosch et al., 2015).
- Design low-fidelity fall back alternatives when technology fails (e.g., paper-based questionnaires instead of computer-based ones) (Lukosch et al., 2015).
- Decide for the type of experiment: field vs. laboratory experiments.

- Select carefully a comparative measure for the control group.
- Decide whether a cover story is needed.
- Select study participants that represent the target group of the research.
- Motivate study participants to take part in the study.

5. Evaluation of the research instrument. The three games of the case studies experienced several challenges in applying the game as a research instrument. Instructions leave room for people to choose among own interpretations and strategies as Donchin (1995, p. 218) states: "It is critical to ensure that the subjects do not exercise their option to adopt strategies that are in conflict with the investigator's model of the task […]". Furthermore, in the evaluation phase differences between individuals in their approaches to the game task should be monitored (Donchin, 1995). This is especially relevant since games are characterized by an inherent flexibility and dynamic. For B.u.S. it was challenging to control the way different pupils played the game. Adding onto this, deciding for the right data analysis method was challenging due to the complex repeated-measurement design (König et al., 2019).

Main criteria of the evaluation, based on the challenges identified for this phase:

- Let players explore the rules of the game (dynamic situation) (Donchin, 1995).
- Log all players' choices and actions (Michael and Chen, 2006).
- Integrate qualitative (e.g., subjective assessments) and quantitative (e.g., physiological) data in the analysis of the data.
- Select 'right' data analysis methods.
- Adapt to the setting of the game play session and its specific conditions (consider confounding variables such as day time, light conditions etc.).
- Reflect whether game and results are valid and conclude with recommendations/transfer back to the real system (Kriz, 2003; van der Kooji et al., 2015).

5. Recommendations for using games as research instruments in transportation

The present paper compared three digital serious games from the transportation sub-systems freight transport, airport management and public transport with each other according to the challenges faced during the phases of requirements analysis, design, implementation, use of games as research instrument and evaluation. The MDA approach was used to analyse the distinct elements of the game, and enabled the researchers to compare the structure of the three games with each other. The novel ReDIRE framework was developed and applied to illustrate possible challenges when using games as research instruments. The subsequent Table 1 lists Do's and Don'ts for this process, and proposes recommendations to the main challenges faced in the specific phases. However, it should be emphasized that transportation is a vast multi- and cross-disciplinary subject and the findings of the three case studies can only be transferred and generalized to a limited amount to other contexts. Yet, the derived recommendations and lessons learned can serve as a starting point and stimulation for the reflection on other serious games used as research tools. Table 1 represents a summary of the main challenges along with our recommendations of Do's and Don'ts when addressing these.

Table 1. Overview of identified main challenges and the derived Do's and Don'ts

Phase	Main challenge	Do's	Don'ts
Requirement analysis	Define the right method	Think about the specific problem the game should address and reflect which type of a serious game can support that.	Do not think that a virtual reality game is the only method of choice. Reflect the pros and cons critically.
	Formulation of a problem statement	Formulate your problem statement as specific as possible.	Do not think about solutions yet but be open to creative ideas.
	Target group	Integrate the target group as early as possible in the design process of a serious game.	Do not believe that target groups are homogeneous. Even though they are from the same sociodemographic stratum they might differ strongly in their gaming experience among others.
	Resource management	If possible, work together with people in an interdisciplinary team with representatives from different disciplines and if possible, practitioners from the field of research.	Do not overestimate the resources that are available
Design concept	Real world reality versus in game reality	Find out what the right degree of realism and abstraction of the complex system for your serious game is.	Do not neglect the degrees of freedom in playing the game; do not limit yourself to assessing physical fidelity as psychological, functional or social fidelity might even be more important.
	Balance of game mechanics/ flow	If possible, adapt the game's difficulty to the players' gaming experience and competencies.	Do not develop a game that is too easy or too difficult.
Implementation	Analysis of problems and debugging	Conduct playtests as many/early as possible. Try to create a vertical slice to get a first impression if the game performs as expected.	Do not underestimate the time for conducting playtests and debugging and polishing the game.
	Validity of a game	Proof the validity of your game with domain experts.	Proof the validity of your game with domain experts.
Research framework planning	Collection of data	Guarantee a careful collection of data.	Do not log and assess only quantitative data from a single source.
	Role of the facilitator	Think about the role of a facilitator.	Do not change the facilitator between different study design conditions to prevent confounding.
	Briefing and Debriefing	Think about a good structure for a workshop consisting of connected parts of briefing, gameplay and debriefing.	Do not just think about the game and forget about the role of the game in the bigger research setting.
Evaluation	Balance between reality and play	Compare results with initial ideas and reflect upon the level of abstraction vs. complexity.	Do not overestimate the transferability of the study results.
	Consider qualitative data	Analyse qualitative data to facilitate the interpretation of quantitative data, especially to understand players' choices and actions.	Do not neglect the degrees of freedom and number of different approaches towards the game that players have when engaging with the game.

1. Requirement analysis. For a proper analysis of the requirements, we recommend to think carefully about which type of a serious game can support which message, and if a game is the right instrument to address the given problem in general. Therefore, a simple list with pros and cons of

using a game versus for instance a simulation can be helpful to make a proper decision for or against a serious game, and which type to use.

Furthermore, we advise to formulate a problem statement as specific as possible. This can be done by using frameworks such as the IDEAS approach developed by Freese and Lukosch (2019). IDEAS is an approach with the aim to consider challenges of today's complex systems and to define a concrete problem statement as a first step of the design process of a valid serious game. IDEAS consists of four steps – **I**nterview(s), **D**iscussion round(s) with **E**xperts, moscow **A**nalysis (Clegg and Barker, 1994) and game**S**torm. Based on IDEAS, one should be able to identify a problem statement which can be addressed with a serious game. Therefore, it is crucial to stay focused on one problem statement per game. Having an unspecific or too vague problem statement can lead to an invalid game and to wrong research results.

In addition to this, the target group(s) should be integrated as early as possible in the design process of a serious game. As written, one characteristic of complex systems is the fact that many actors interact with each other. To guarantee their involvement with the aim to make processes more transparent and to establish a trustful working environment, workshops and participatory brainstorm sessions can be organized, especially at the beginning of a project. Our experiences show that the involvement of actors and project members lead to more acceptance and trust in a serious game. If possible, working together with people in an interdisciplinary team with colleagues from different disciplines and practitioners from the field of research, is another recommendation we would like to add.

Last but not least, the resources need to be checked carefully without an overestimation of time and finances. The relationship between time, costs and quality has already been taken into account by the magic triangle approach of Kuster et al. (2015), which has been developed for project management-related topics.

2. Design Concept. With regard to the second category, the most challenging aspect is to figure out what the right degree of realism, or fidelity, for a serious game is. Therefore, we recommend to consider the research question you want to answer, the stakeholders that are involved or the target group you have, the outcome you want to desire and the resources and requirements that are available (Freese et al., 2018). In addition, some work has been done on the physical fidelity of serious games, referring to the correct representation of the audio-visual layer of reality. Yet, it shows that functional, social and psychological fidelity can be even more important for the validity of the game (Lukosch et al., 2019). It is of outermost importance to address the challenge of complexity reduction in the design concept (Learmonth et al., 2011). The dynamically interacting components in both natural and human dimensions of complex transport system must be simplified in order to create a playable serious game. Yet, important characteristics of the systems should be considered in the game model.

Moreover, the game should not be too easy or too difficult for its target group. Here, conducting playtests considering feedback loops and back and forth steps is helpful to balance the flow. It can beneficial to either have a large, diverse test group, or conduct play tests with different groups (think of age, cultural background, gender, educational level and so forth). Remind that a serious game should be challenging, but also an engaging thing to do.

3. Implementation. Regarding the third category, we learned that it is important to organize as many and early playtests with as many individual players as possible. Try to create a vertical slice to get a first impression whether the game performed as expected. The aim of having theses playtests is to debug and polish the game. It is not necessary to make everything perfect before testing. Therefore, you can use placeholder and dummies for first test runs. Playtests, in general, costs resources like time and money. In the implementation phase, the game designer always faces the challenge of the trade-off between time, costs and quality according to the magic triangle (Kuster et al., 2015).

Furthermore, you should proof the validity of your game. Checklists, for instance the one developed by Peters and Van de Westelaken (2011), can be used to check the validity of serious games used as a research instrument. In addition to this, interviews with experts can be conducted and used as face validation. Implementation of the game also relates to knowing the context in which the game will be played, and developing a suitable game session around the game and the research objective. The availability of experts is important to design a valuable session. Using additional research instruments might be needed in order to gather rich data that answer your research question.

Another advice we would like to give is that it is not just about the game itself. Think about a good structure for a workshop consisting of a briefing, gameplay, and debriefing. According to Crookall (2010), a debriefing is the most important part of a gameplay session. To guarantee the transfer of lessons learned of the gameplay into the real working environment of people, a debriefing is crucial and needed (Crookall, 2010). A debriefing is a reflection phase where players and facilitator(s) talk about the experienced emotions, events and experiences, but also about the connection to the everyday life of the players (Bartschat and Schwägele, 2014). When serious games are used as research instruments, the debriefing phase not only fosters the engagement and learning of the player, but can provide valuable data for research purposes beyond the gameplay process itself. The fact that you embed your game in a session with briefing and de-briefing strengthens its valid relationship with reality.

4. Research framework planning. When using games as research instrument with the aim to analyse complex systems characterized by complexity and uncertainty, the use of a serious research game needs to be standardized as much as possible to guarantee criteria, such as reliability and objective and to reduce facilitator-related or experimental biases. Regarding the fourth category, you should guarantee a careful collection of data. Think about the different types of data and which of them could answer your research question. Use engaging, validated research instruments such as short questionnaires or a challenging multitasking tool and combine them with the game itself. This combination can create a rich session for participants, and allows a rich data collection. Think also about a mixed-methods approach – digital games provide you with a huge amount of data suitable for quantitative analysis methods. Focus group interviews with players might reveal valuable qualitative data on the decisions and actions players carried out during gameplay.

In addition to this, think about the role of the facilitator and the influence he/she can have as well. Consider the side effects of the game that were not planned as desired results of the game.

5. Evaluation. We see from our analyses, that the greatest benefit of serious games – their flexibility – at the same time implies their greatest challenge. Serious games offer a higher degree of freedom due to the fact that they represent a simplified model of a real system in addition to the use of engaging game elements. Game developers and researchers have no full control over the way how players perceive and play the game. The perceptions of individuals of the game are influenced by their previous experiences, play style, and the gaming setting among others (Antonioni et al., 2019). Thus, the inherent flexibility and dynamics of games poses a challenge to the researcher that should not be underestimated in the entire game development process and application of the serious game for research purposes. Overall, it is advisable that the researchers that aim to use a game for research purposes develop the game themselves, or at least fully understand and largely control the game environment. Donchin (1995, p. 218) adds on this: "A game is useful as a research tool if, and only if, the investigator can exercise systematic control over the game's parameters." This way, the game can be developed for the specific purpose and game parameters can be adapted to the game's aims whereas side effects can be controlled for. Yet, the flexibility and heterogeneity in applying the game stays a factor of uncertainty and variance that should be taken into account. Thus, logging all players' choices and actions seems essential for studying the players' behaviour and derive valid conclusions.

6. Conclusions and outlook

With the present paper we aim to answer the question what criteria need to be considered for the design, development and use of serious games as transportation research instruments. We presented three digital serious games based on the novel comparative use of the MDA approach from the transportation sub-systems freight transport, airport management and public transport and showed how we used them as research instruments.

Serious games are valuable as transportation research instruments in different sub-systems. The decision for using a serious game or any other method is always one of the very first challenges and depends on many factors, such as the specific research question and/or learning goal. As transportation is a complex system and a serious game represents a simplified model of such system, one might ask if games are an appropriate tool to analyse and design such systems. Many studies (e.g., Antle et al., 2014; Ariffin et al., 2010; Ebnali et al., 2019; Gonçalves et al., 2014; Rosetti et al., 2013; Van den Hoogen et al., 2012) have already discussed this topic and came to the conclusion that especially games are a suitable tool to analyse human behaviour in a safe environment. This is one of the advantages games have in comparison with other methods. They offer players a safe environment that allows the exploration of consequences of certain decisions without (expecting) any negative consequences. However, and with regard to the use of games as research instruments, it is worth to say that games are less rigorous than other methods, as games include a "large number of variables that are hardly to be controlled in a dynamic situation of game play" (Lukosch et al., 2018, p. 284). Every player brings their own background, experiences and expectations that influence the game process. In order to allow for an engaging play experience, the game itself has to show a certain degree of freedom of choice and action. So, many variables exist that need to be controlled.

In addition to this, we showed that the design and development of a serious game as research instrument is linked to many challenges. Based on the cross-case-analysis and a comparison of existing game design approaches, we developed the ReDIRE framework. This framework consists of five clusters – requirements analysis, design, implementation, usage of games as research instrument and evaluation phase – that can be used to go step-by-step through the design, development process and the process of using a serious game as a research instrument. Based on a literature and game analysis, we described more specific challenges and lessons learned and derived practical recommendations to support researchers and practitioners in applying serious games as research instruments in transportation.

Transportation is one example of a complex systems that is a vast multi- and cross-disciplinary subject. The discussed findings can be generalized to a limited amount to other contexts where complex systems show similar characteristics as discussed in this article. However, the derived practical recommendations can be seen as a starting point for the reflections of other serious research tools and further research in this domain is needed to analyse the comparative use of the MDA, validate the novel ReDIRE framework or extend the derived list of challenges.

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