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Tools to help teachers and designers complete individual tasks when co-designing industrial engineering games – Application to the design of an innovation management game

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Abstract: Serious games (SGs) offer an engaging format for teaching industrial engineering (IE) methodologies. IE methodologies involve people following a typical process in a given set of conditions to design, improve and install integrated systems, which are easily scripted into gameplay. The scholarship has proposed co-design approaches to facilitate collaboration between teachers and SG designers. However, teachers are not always ready to engage, and game designers can readily create SG elements more rapidly on their own. We propose a co-design framework to better distinguish the roles of teachers and game designers and also four tools for them to better embed relevant expertise in the SG design process. A first tool is a domain decomposition model, which helps teachers create the knowledge repository for a given IE methodology. Then, a specification vector is provided that helps define clear learning objectives. The third tool is a mapping table that inspires designers to build gaming elements based on the designated learning objectives. The final tool is a verification table that serves to help check whether the learning experience offered by a SG is aligned with its learning objectives. A game on innovation management was designed that adopts the co-design framework. It was tested in three sessions with 23 players, resulting in a playful learning experience.

Keywords: serious games; industrial engineering methodologies; co-design; learning objectives

1. Introduction to serious games in industrial engineering

Serious Games (SGs) refer to ‘all processes designed to learn and experiment without necessarily using the support of video games’ (Mossoux et al., 2016). SGs have been widely used in various higher and executive education disciplines, as they can provide playful, motivating and engaging learning experiences (Zhonggen, 2019). SGs as educational products have a full lifecycle, including conceptual design, development, validation, deployment, and iterative refinement (Alonso-Fernandez et al., 2017). Various frameworks/models/methodologies that guide design and development processes have been proposed to remedy the complexity of SG design. Table 1 briefly introduces five of them, each of which clarifies an exhaustive process consisting of different stage.

Table 1. Design frameworks/models/methodologies for SGs

| Reference | Contribution |
|--------------------------|--|
| [Barbosa et al., 2014] | A design methodology that facilitates the integration of educational content while keeping the fun factor of SGs. |
| [Carvalho et al., 2015] | A design model ‘ATMSG’ based on the activity theory. It supports a systematic and detailed representation of SGs and depicts how game elements contribute to the desired pedagogical goals. |
| [Callaghan et al., 2018] | A framework that extends the ‘ATMSG’ model with an additional game trace layer in the engineering education context. It aids the instructor in mapping actions to the appropriate category of identifiable game traces and determining which information needs to be extracted for game analytics. |
| [Silva, 2020] | A methodology to design SGs that facilitate communication between design team members. It illustrates all the main steps needed to define the learning mechanisms, which starts with the choice of the topic of the game and ends with the user experience. |
| [Urgo et al., 2022] | A framework for the design of SGs in engineering education. It focuses on the definition of intended learning outcomes. |

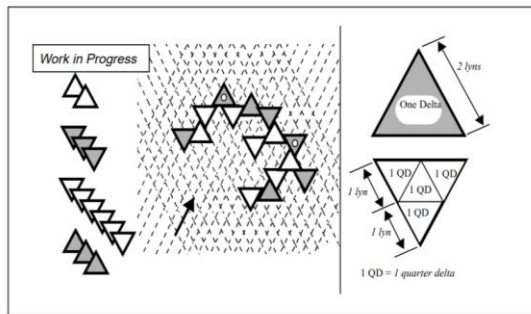
To integrate entertainment and educational features into SGs, the design team must possess both instructional expertise and game expertise (Marne et al., 2012a). That is why more and more SG designers are bringing the co-design approach into the SGs design process. Teachers and end-users are invited to create and even test the game. However, even trained teachers still face problems when designing a SG (McMahon, 2009). Therefore, they need additional guidance to complete assigned tasks.

The scholarship has proposed many frameworks and methods to solve the collaboration problems between teachers and SG designers. Ibáñez et al. (2011) proposed a conceptual framework based on six independent facets involved in SG development that serves as a common language to improve communication between teachers and SG designers. This framework was then further developed by Marne et al. (2012b) to create

a Design Pattern Library, which provides a detailed description and several instances for each facet. For example, the instance ‘Quick feedback’ is considered a way for players to interact with the game world. It enables teachers to understand how to present learning materials and appropriate guidance to players in a SG. Other studies have focused on organizational configurations and divisions of work for designing SGs. Perini et al. (2018) applied an iterative co-design process to design a manufacturing engineering game in which teachers, subject matter experts, and students were brought together to systematically involved from concept to refinement of the solution through field testing and evaluation in real classroom settings. Various stakeholders solve all problems and conflicts through timely communication. The design-based research (DBR) methodology (Plumettaz-Sieber et al., 2019) defines the roles of researchers, teachers and SGs designers in a co-design process. When applying DBR, they found that the availability of team members greatly affected the design progress. This is because teachers are often required to define the game’s learning objectives and also join the conceptual design. However, teachers are not always ready to engage, and experienced game designers can readily create SG elements more rapidly on their own. *There is a lack of a means to facilitate collaboration between teachers and designers while ensuring that everyone is doing what they are skilled for.*

Industrial engineering (IE) is the branch of engineering concerned with designing, improving, and installing integrated systems (IISE, 2022). IE methodologies study the principles, practises and procedures that facilitate the above-mentioned activities. As Author (2021) discussed, SGs can serve as valuable tools for introducing IE methodologies as they guarantee intrinsic motivation and provide situated learning. In addition, it is very natural to use SGs for teaching IE methodologies, because IE methodologies involve people following a typical process in a given set of conditions to achieve collective performances. It is therefore conceivable that a SG in IE is easily scriptable. And it is true that SGs have been applied in many situations involving IE methodologies. As early as the 1980s, Prof. Louis Bucciarelli from the MIT created a Delta Design game (Figure 1), which helps undergraduate learners cultivate communication skills during collaborative design. EKIT’EKO, created by Alvarez et al. (2014), is a simulation-strategy game (Figure 1) where players are asked to develop new innovative products in a sustainable way.

Congratulations! You are now a member of an expert design team. Your collective task will be to design a new residence suitable for inhabitants of the imaginary Deltoid plane....



(a) Delta Design



(b) EKIT'EKO

Figure 1. Examples of SGs in the IE domain

As mentioned earlier, existing co-design approaches force teachers to be too involved in tasks that they are not good at without providing sufficient guidance, such as generating game ideas. To relieve teachers' burden and allow them to communicate smoothly with game designers to ensure the game quality, we are committed to tackling the research questions of *how to facilitate collaboration between teachers (especially in IE) and game designers while ensuring that both keep their field of expertise, and how to make them do what they are good at without forcing them to acquire too much of each other's expertise*. Figure 2 describes the context adopted to address these challenges, a collaboration framework that simplifies the roles of teachers and game designers. It covers four typical phases of SG design that have been extensively discussed in the literature. The first two stages correspond to the phase *Definition of learning objectives*, while the remaining three stages correspond to *Game design*, *Verification*, and *Validation* in turn. The four contributions (tools) of the co-design framework are:

- A *domain decomposition model* for teachers to create a knowledge repository of the considered IE methodology.
- A *specification vector* to express the IE methodology knowledge acquisition objectives and expected learning experience.
- A *mapping table* between the domain decomposition model and the SG design language model to help SG designers derive the SG architecture based on the defined learning objectives.
- A *verification table of player experience* to cross-test against the specification vector to help teachers verify that the game delivers the expected learning experience.

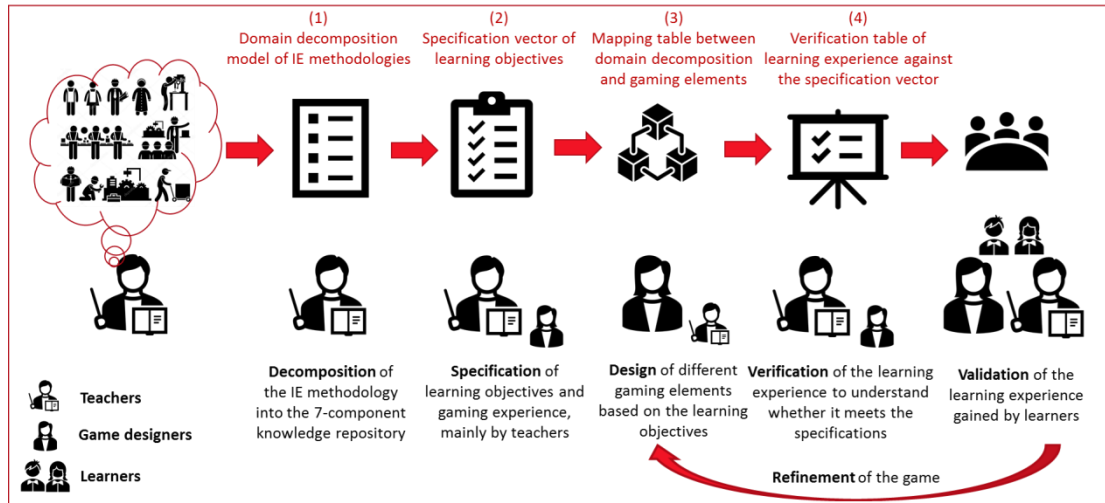


Figure 2. A SG co-design framework between teachers and game designers to simplify the roles of both

The remainder of this paper proceeds as follows. Section 2 presents the research methodology. Sections 3 to 8 introduce and illustrate the proposed co-design framework and its four contributions by designing an IE game. Section 9 discusses the results and provides conclusions.

2. Research methodology

Design Research Methodology guidelines were carefully followed for this empirical study (Blessing & Chakrabarti, 2009). The main methodological choices are reported below.

The proposed co-design framework is applied to the *Radical Innovation Design* (RID) methodology (Author, 2020), which has been validated in various industrial and business sectors. RID is a structured innovative design methodology that guides innovators who want to systematically explore users' problems and unstated needs and evaluate which of them most urgently demand innovation given the (in)effectiveness of the existing solutions (Author, 2020). The study is an in-depth, single-case, non-comparative work aiming at delivering a prototype SG (named RID game) while following a systematic design process. RID game is expected to be used for higher and executive education.

The *unit of analysis* is the four phases of the SG design process between teachers and game designers. The *task* of SG design was set in a realistic manner in research conditions but for educational purposes.

The researcher (the first author) was involved as a *participant-observer* in the different phases of the SG design. He played the role of a *game designer* (mobilizing acquired expertise in game design). However, the researcher played the role of *observer* for the

validation phase with groups of players.

The SG design team enlisted three *RID teachers*, one of them being the *inventor* of RID, and one researcher in the role of the *game designer*, who organized and facilitated a series of twelve design sessions (3hrs per session).

Once the SG prototype was set (12 design sessions in 7-month), *three validation sessions* were organized: one for experienced people (6 innovation professionals who are familiar with RID) and the other two for beginners (17 engineering students who are unfamiliar with RID). As experienced people are more likely to offer suggestions on ways to improve the RID game's learning experience it was decided to let them experience it first. The inventor of RID served as the trainer for the sessions.

3. Domain decomposition and definition of learning objectives

Table 2 proposes a domain decomposition model of IE methodologies, which allows arranging knowledge items on a given IE methodology into seven categories: *objectives of the methodology* and its *processes, performances, competencies, principles, concepts*, and *methods & tools*. This model helps teachers create a knowledge repository needed to define the learning objectives of IE games. The model was previously developed by 15 experts and has since been applied to describe 12 IE methodologies, for which results can be consulted online (Author, 2021).

Although our model and the Industrial and Systems Engineering Body of Knowledge (IISEBoK) proposed by the Institute of Industrial & Systems Engineers (2023) are dedicated to teasing out the knowledge of the IE domain, their applications and scopes are different. The IISEBoK outlines fourteen IE knowledge areas and defines a list of concepts to be known to achieve mastery of each area. It may serve as a repository for teachers to check the completeness of an IE course teaching content. Our model provides a specific method for organizing the teaching content of an IE methodology and defining the pedagogical objectives.

Table 2. Domain decomposition model of IE methodologies

| Knowledge category | Definition |
|--------------------------------------|--|
| Objectives of the methodology | The history of the targeted IE methodology and the main problem it solves. |
| Processes | <p>The main authoritative references on the methodology.</p> <p>Defines a series of interrelated tasks for designing, improving and installing integrated systems of people, materials, information, equipment, and energy. These tasks may be done by people, nature, or machines, using various resources. Industrial projects may serve as examples to illustrate the process. This category also includes describing the organizational, contractual or sociological contexts of applying the methodology. It has three sub-categories:</p> <ul style="list-style-type: none"> • The process itself (tasks, deliverables, people, etc.). • The practical illustrations (examples) of how to use the methodology to solve industrial problems. • The organizational, contractual or sociological contexts in which the methodology is to be applied. |
| Performances | <p>The performances field can cover three different aspects:</p> <ul style="list-style-type: none"> • The criteria or indicators adopted by the IE methodology to ensure that a set of activities and outputs meets an organization's goals in an effective and efficient manner. • The merit, worth, and advantages of an IE methodology compared to other methodologies used for the same research topics. • The limitations or disadvantages of the methodology. |
| Competencies | <p>The skills, personal characteristics, and behaviours developed or needed when performing tasks that design, improve, and install integrated systems of people, materials, information, equipment, and energy. It has two sub-categories:</p> <ul style="list-style-type: none"> • General competencies required any IE methodology: teamwork, communication, independent thinking, etc. • Specific competencies required by the targeted IE methodology. |
| Principles | An idea or rule respected by the IE methodology. |
| Concepts | Abstract ideas or general notions that are understood to be the fundamental building blocks of the targeted IE methodology. |
| Methods & Tools | <p>Two sub-categories:</p> <ul style="list-style-type: none"> • Methods are prescribed processes for completing tasks embedded in the targeted IE methodology. • Tools are software or techniques used to extend the ability of an individual to perform the relevant tasks. |

In the engineering education literature, learning objectives are roughly divided into *knowledge* and *competence* (Pusca & Northwood, 2016), but the proposed domain decomposition model offers a more systematic template. The remaining five new categories in the domain decomposition model can be considered sub-categories to help differentiate knowledge on a given IE methodology. When designing the game,

teachers first need to identify all the knowledge items of the targeted IE methodology and then classify them based on the domain decomposition model. Table 3 summarizes the decomposition of the RID methodology, which serves as a knowledge base to define the learning objectives of the RID game.

Table 3. The knowledge decomposition of RID

| Knowledge category | Knowledge item |
|-------------------------------------|---|
| Objective of the methodology | The objective is to innovate on an activity from the viewpoint of its beneficiaries via a structured Design Thinking process, visual management and decision-making tools, and project and knowledge management facilities |
| Processes | <ul style="list-style-type: none"> • At a high level, the RID process breaks down into three stages: 1) Observe and learn, 2) Explore and decide, 3) Ideate and design • A more detailed 8-stage and x-shaped process • The algorithmic workflow for segmenting the activity |
| Performances | <ul style="list-style-type: none"> • The performances in driving the RID process • The comparative performances of RID vs other innovation methodologies |
| Competencies | A series of 29 general innovation competencies required by RID Examples include curiosity, creativity, systems thinking skills, and more |
| Principles | <ul style="list-style-type: none"> • RID philosophy of innovation and the sources of inspiration of innovation • Transformation of a user activity system • Thinking inside the box • Reframing by the activity • Consider the innovation activity as a production process • Traceability on the innovation process |
| Concepts | RID relies on 11 concepts, like RID disruption and the four dimensions of activity |
| Methods & Tools | RID includes eight methods and tools, such as Business Model Canvas-RID and RID creativity tool |

For the next step, teachers are recommended to adopt the *personas* method to understand and characterize players' archetypes. The rationale is that the method could help better identify what they want to learn about the targeted methodology. The design team of the RID game intended to develop a minimum viable product to satisfy all users and keep the possibility of proposing configurable SGs adapted to a specific persona. Three 'student' user personas were created, i.e. an engineering student, a design student, and a business student, since they are the primary groups of students participating in the RID training. Three professional personas were also proposed: a user experience designer, a business consultant, and an entrepreneur. They are likely to be attracted by RID due to its obvious utility in their professional spheres. Figure 3 shows the 'entrepreneur' persona.



Figure 3. 'Entrepreneur' user persona

After creating all the relevant personas, teachers need to prioritize knowledge items according to each persona's needs and describe the corresponding learning objectives. An intensity scale is proposed in Table 4 for completing the task. It has seven grades and combines the Numerical Rating Scale (Treiblmaier & Filzmoser, 2011) and measurable verbs used to express learning outcomes (Stanny, 2016). Grade 0 means no learning objective related to this item, while grades 1 to 6 correspond to the six levels of learning borrowed from Bloom's taxonomy (Krathwohl & Anderson, 2009).

Table 4. Intensity of the specified learning objectives for IE games

| Grade | Definition | |
|-------|---|---|
| | During the game | After the game |
| 0 | - | - |
| 1 | The item should be mentioned in the game but not precisely explained | A player could memorize related information and gain interest in learning more about this knowledge item without having to fully understand it. |
| 2 | The item should be sufficiently explained but will not be practiced by players | A player could explain its definition, principle and interest in his or her own words |
| 3 | The item is precisely explained and players must at least practice it in a simplified manner | A player could apply it simply, or at least to frame it differently in the real-world situation |
| 4 | The item is precisely explained and players must take initiatives to analyse the game situation in order to categorize and contrast the possible solutions and make decisions | A player could analyse the related real-world situation in order to categorize and contrast the possible solutions and make a decision |
| 5 | The item is practiced in a non-trivial manner and players must evaluate the value of the item in the game situation | A player could apply the item differently, argue for the best solution to choose, and synthesize the whole action |
| 6 | The item is practiced in a non-trivial manner and players could create around the item in the game situation | A player could be creative with the item, which means that the player know when and how to apply the item in a new way to clearly formulate the expected outcomes |

The domain decomposition model and the intensity scale were applied to rate a vector of specifications of the RID game learning objectives. The RID inventor first rated the intensity of RID items for each persona and wrote down all the supporting evidence. The design team then organized a discussion session with the same purpose, involving two other RID teachers. The three teachers reached a consensus and thus determined the final learning objectives of the RID game. The game's purpose is to provide players with a basic understanding of RID. Only the first six grades (0 to 5) of the intensity scale were applied to avoid setting overly ambitious educational goals. Figure 4 shows part of the results (see Author (2021) for more details). Teachers can follow the above approach by first identifying learning objectives in a concise form and then transcribing them into detailed text. Game designers need to prepare for conceiving game elements by communicating with teachers to understand the learning objectives fully.

| Knowledge category | Obj | Processes | | | | | | | | | | Methods & tools | | | | Principles | | | | | | | | |
|----------------------------|-------------------|-------------------|-------------------------|----------|--------------|-------------------|------------------------|----------------------------|----------------|------|--------------------|----------------------|----------------|--------------------|---------|----------------|--------------|-------------------------|-------------------------|-------------------------|-------------------|----------------------|--------------------------|--------------------------------------|
| RID items | Objectives of RID | General breakdown | Detailed representation | Actigram | RID platform | Usage-driven rep. | Activity centered rep. | Transformation of activity | Data streaming | UDIP | Production process | Prob and Sol duality | DSM, YB method | Ambition perimeter | BMC-RID | RID creativity | UNPC monitor | Rearranging by problems | Rearranging by activity | Thinking inside the box | Nature of an idea | Intensity of an idea | Philosophy of innovation | Activity field & rules of classicism |
| Engineering student | 5 | 5 | 1 | 2 | 0 | 0 | 3 | 3 | 1 | 2 | 4 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 1 | 1 | 4 | 3 | 0 | |
| Business student | 5 | 5 | 1 | 2 | 0 | 0 | 3 | 3 | 1 | 2 | 4 | 2 | 3 | 3 | 5 | 3 | 3 | 2 | 2 | 1 | 1 | 4 | 3 | 0 |
| Design student | 5 | 5 | 1 | 2 | 0 | 0 | 3 | 3 | 1 | 2 | 4 | 2 | 3 | 3 | 3 | 4 | 3 | 2 | 2 | 1 | 1 | 4 | 3 | 0 |
| Mobile apps designer | 5 | 5 | 1 | 2 | 0 | 0 | 3 | 3 | 1 | 2 | 4 | 2 | 3 | 5 | 3 | 3 | 3 | 1 | 1 | 1 | 3 | 4 | 2 | 0 |
| Innovation consultant | 5 | 5 | 1 | 2 | 0 | 0 | 3 | 3 | 1 | 2 | 4 | 2 | 3 | 5 | 5 | 3 | 3 | 1 | 1 | 1 | 3 | 4 | 2 | 0 |
| Startup founder | 5 | 5 | 1 | 2 | 0 | 0 | 3 | 3 | 1 | 2 | 4 | 2 | 3 | 5 | 5 | 3 | 3 | 1 | 1 | 1 | 3 | 4 | 2 | 0 |
| Common learning objectives | 5 | 5 | 1 | 2 | 0 | 0 | 3 | 3 | 1 | 2 | 4 | 2 | 3 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 | 4 | 2 | 0 |

Figure 4. Specification vector of learning objectives for the RID game

4. Design language model of SGs

According to the learning objectives, designers generate game ideas and then create prototypes. This section defines a design language of SGs based on the state of the art to help teachers understand game ideas to provide feedback. It includes all the serious game design objects discovered so far, which should serve as a tool to facilitate communication between teachers and game designers.

4.1 Literature review of SG design objects and architectures

The SG system comprises various design objects that can be regarded as a set of building blocks shared by SGs. Maheu-Cadotte et al. (2018) think that design objects are game mechanics. Game mechanics have been broadly understood as a way to summarize game rules. This view is limited, as ‘story’ is not a game mechanic but appears in every serious game. Lameris et al. (2017) distinguished design objects into game mechanics and learning attributes. Learning attributes are mechanics that facilitate learning in games. This classification is not detailed enough to use it to break down and further analyse SGs.

The well-known serious game design assessment (SGDA) framework (Mitgutsch & Alvarado, 2012) identifies six essential components of the structure underlying a SG: learning objectives, content, story, game mechanics, aesthetics, and framing. It helps IE teachers understand the composition of a SG. Razali et al. (2022) proposed a checklist of 13 design objects: goal, narrative content, rules, scope, type, aesthetic, player’s character, game mode, level design, quiz, reward, challenge, and rank. Although this taxonomy appears to be more exhaustive, it merely lists some instances of the objects within the SGDA framework. For example, rules, type, player’s character, game mode, quiz, reward, and rank are all linked with ‘game mechanics.’ Most scholarship has only used the SGDA framework to analyse SGs, here we employ it as the backbone for establishing the SG design language.

The architecture of a SG determines the arrangement of and relations between gaming elements. In the field of SGs, a game is usually considered to be composed of different game levels (Barbosa et al., 2014; Chua, 2017). Each level poses players different tasks that they need to complete to advance in the game. Decomposing the entire game system's design into the design of different levels and then merging the results help to reduce the complexity and ease the integration of educational content in the game. A game level may further consist of one or more game challenges (Libe et al., 2020) defined in the following subsection.

4.2 Building a design language model for SGs

The design language model includes eight generic design elements, five of which are from the SGDA framework, i.e. *learning objectives*, *story*, *gameplay*, *information*, and *aesthetics*, and the other three are *design constraints*, *evaluation*, and *game props*. First of all, SGs are expected to perform in a predefined usage situation. *Design constraints* shape the usage situation and help narrow down choices when creating a game. The RID game was expected to be employed in one-day innovation management training and suitable for all six identified personas. Second, *evaluation* is fundamental to the process, as it is a significant way to provide feedback on the choices made by a player, and it has a major impact on player satisfaction. Evaluations in SGs commonly use a scoring system (Arif et al., 2021), which intuitively reflects players' performances in the form of numbers to stimulate their motivation. Third, *game props* are artefacts that operate at each level and are closely linked to other gaming elements. For example, cards are game props that carry information as well as to materialize the gameplay. The eight gaming elements define a template for designers to complete when creating a new SG's three systematic design layers (Author, 2021). Table 5 defines each object of the proposed design language model.

Table 5. Design language model for SGs

| Nature | Object | Definition |
|------------------------|---------------------|---|
| Architecture | System layer | The game is treated as a coherent and consistent system |
| | Level layer | Game levels are the different parts that constitute the pathway players can follow in the game |
| | Challenge layer | A task that demands a player's mental or physical effort to successfully complete |
| Design elements | Learning objectives | The designer's intent for the SG design |
| | Design constraints | A list of pre-assumptions, which describe the targeted users and when, where, and how these users will apply the game |
| | Story | The game's whole background story |
| | Gameplay | A set of core game mechanics that determine a game's overall rules |
| | Information | The information offered and used in the game, which needs to directly or indirectly facilitate the achievement of learning objectives |
| | Aesthetics | For board games, aesthetics is reflected in the visual appearance of game props |
| | Game props | The design artefacts that derive from all the other design elements to materialize the game in reality |
| | Evaluation | The way to measure players' performances and to provide them with feedback |

5. Mapping between knowledge categories and gaming elements

The previous two sections introduce a) a domain decomposition model of IE methodologies and b) a SG design language model. This section articulates these two contributions to explain how the learning objectives of a SG inspire the process of designing gaming elements in the context of IE education. The results help game designers better grasp the learning objectives and give them basic inspiration for conceptualizing each gaming element.

5.1 Literature review on mapping learning and game mechanics

A few studies have focused on mapping learning mechanics (LM) and game mechanics (GM) to balance fun and learning in SGs. Arnab et al. (2015) proposed a Learning Mechanics-Game Mechanics (LM-GM) model to support SG design by translating learning objectives into gameplay. It clarifies the interrelations between a series of LM and GM that are abstracted from the literature. Designers first need to choose an effective LM for certain instructional content, then query the map to find one or more relevant GM based on which they will ultimately design the gameplay. Many researchers have adapted and applied the LM-GM model to support not only the design

but also the analysis and the assessment of SGs (Callaghan et al., 2016; Maarek et al., 2019; Kulshrestha et al., 2021; Kuswandi & Fadhli, 2022). For example, Kuswandi & Fadhli (2022) performed an LM-GM-based analysis to map the pedagogical elements/learning outcomes to game elements when designing the core loop of a game on electrical engineering.

Similar to the LM-GM model, the ATMSG model (Carvalho et al., 2015) decomposes each game activity of the player into a series of actions, and each action has the corresponding gaming or learning attribute. In addition, the ATMSG model also incorporates the analysis of the learning objectives of each action, which can guide designers and teachers to design the learning behaviours and game behaviours that players should perform according to each learning objective.

The LM-GM and ATMSG models are more analysis-oriented, while the methodology of Silva (2020) is more design-oriented. He decomposed the SG design into gaming and learning layer designs. To design gaming layers, the methodology focuses on three elements: story, design constraints, and gameplay. The methodology recommends 12 commonly used LM and their related mini-games for the design of learning layers to integrate the designated instructional content into a SG.

All the studies identified explore *gameplay (game mechanics)* design purely in terms of *SG learning objectives (learning mechanics)* without discussing other game design objects. In parallel, a lack of exemplification prevents teachers and designers from establishing a mutual understanding and makes it difficult for them to communicate game ideas.

5.2 Building a mapping table between knowledge categories and gaming

elements

To build on the relevant extant scholarship and address its limitations, Figure 5 proposes a mapping table between knowledge categories of the IE methodology and the gaming elements. The table is instantiated in Section 6 and verified and validated in Sections 7 and 8.

| | Objectives | Processes | Performances | Competencies | Principles | Concepts | Methods & tools |
|------------------------------------|------------|-----------|--------------|--------------|------------|----------|-----------------|
| Learning objectives | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Story | ■ | | | | ■ | | |
| Gameplay | | ■ | | | ■ | ■ | |
| Information | | ■ | ■ | ■ | ■ | ■ | ■ |
| Aesthetics & Game props | | ■ | | | | | |
| Evaluation | | | ■ | ■ | | | |

Figure 5. Mapping table between knowledge categories and gaming elements

Design constraints are predetermined descriptions of the game’s target audience and how it will be used, which have nothing to do with the IE methodology itself. In addition, game props are often vehicles for aesthetics, so the table merges these two elements.

Learning objectives

An IE game aims to deliver a convincing and engaging user experience that proves the usefulness of the methodology and the circumstances in which it can be applied. Further, the *learning objectives* can relate to any of the *seven knowledge categories*. SG designers are advised to first utilize the domain decomposition model to describe the targeted IE methodology and then choose and prioritize the knowledge items they want to let the user learn. As described earlier, the learning objectives of the RID game are defined based on the different categories of RID items.

Information

The *learning objectives* of the SG can help deduce the *information* that should appear in the game. The ‘general breakdown’ (Author, 2016) is a crucial knowledge item to be taught in the RID game. The game should therefore present the four sub-processes ‘Knowledge design’, ‘Problem design’, ‘Solution design’, and ‘Business design’, and introduce the main tasks within each sub-process.

Story

SGs allow players to acquire and practice knowledge when immersing in the game scenarios that imitate reality. To ensure the authenticity of a SG, its *story*’s design should fit with the *principles* of the IE methodology in reality. For instance, one of the essential principles of RID is the ‘Intensity of idea’, which dictates that a radical innovation necessarily improves user activity. Therefore, ‘urban mobility’ was chosen as the theme of the RID game exemplified here to reflect this principle. It is one of the people’s daily activities, and solving the problems people encounter when moving around the city is bound to improve their life.

A *story* conceived based on the *objectives of the methodology* is the foundation for creating an active learning experience. The objective of RID is to innovate on an activity with a structured Design Thinking process, visual management and decision-making tools, as well as project and knowledge management facilities. The RID game's story was designed based on a virtual innovation project, which enables players to put RID into practice. Players, who in the game act as companies within the mobility ecosystem, are responsible for developing solutions for mobility users and business opportunities for their own companies.

Evaluation

IE methodologies usually contain some *performance* indicators to *evaluate* the results obtained. These indicators are also useful for measuring players' performances in SGs. For example, an indicator applied in RID is 'Value buckets.' Teachers first compute the matrix of value buckets of the urban mobility project, and then use it to evaluate players' performances by scoring their selected value buckets.

Competencies are usually the learning objectives of IE games. Designers need to consider measuring changes in players' competencies throughout the play. A competence required by RID is knowledge management skills. Teachers can evaluate players' performance in the RID game by observing whether they manage to choose effective investigation strategies for gathering sufficient project-related knowledge.

Aesthetics & Game props

For an IE methodology, the graphical representations of the *processes* involved may inspire the design of the *game props*, especially the game board. These representations vividly describe how the methodology is applied to carry out IE activities. The game board of an IE game should depict the player's entire game journey. For example, the *information* and *aesthetics* of the RID game board were designed based on the 'general breakdown'. Players can visualize the game's progress by moving their tokens around the game board.

Gameplay

The *gameplay* of an IE game can be scripted based on *processes* that detail how people complete relevant tasks in reality and *principles* that detail the rules. In addition, *concepts* deeply influence the design of the *gameplay*. Each IE methodology contains its specialized vocabulary. Designers need to design the game rules to allow players to receive and utilize these *concepts* naturally.

The basic *gameplay* of the RID game was created based on two *learning objectives*: 'general breakdown' and 'four value-bucket dimensions'. The former defines the game's structure and governs the players' expected behaviours and objectives in each

game level. For example, the third game level, 'Knowledge design & Problem design,' requires players to collect information about urban mobility through investigation to discover travellers' problems. The four value-bucket dimensions further refine the gameplay, as it requires players to categorize the information collected into four categories: user profile, usage situation, problem, and existing solution. Players can then practice the 'Dependency Structure Modelling-Value Bucket' (DSM-VB) (Author, 2020) method to identify important value buckets. An important value bucket is a major mobility issue met by a category of people that frequently arises when moving around the city and which existing transportation modes fail to address effectively.

6. Deriving the architecture of the Radical Innovation Design game

The learning objectives shown in Figure 4 served as a guide for designing the RID game. To simplify the game's design, the design team adopted four strategies and progressively derived the architecture of the RID game based on the mapping table between knowledge categories and gaming elements.

- Consider the learning objectives of levels 4 and 5 as the crucial knowledge items to teach and which should be used first to influence the system layer.
- The less important objectives can be covered when describing the level and challenge layers.
- The gaming elements of the system layer are designed first and then used as the foundation to design the other two layers.
- To quickly test the effectiveness of the SG design framework in Author (2021), the level and challenge layers are designed simultaneously to speed up the design process.

The design of the system layer started with a review of learning objectives. The team then accomplished two tasks: 1) describing the gaming elements of the system layer; 2) planning the system layout (game levels that constitute the game) and the relationships between the game levels.

The system layout of the RID game was planned according to an important learning objective, i.e. 'general breakdown'. The game comprises five successive levels. It starts with a briefing session introducing game rules (Level 1) and ends with a debriefing session to evaluate players' performance (Level 5). The middle three levels (levels 2 to 4) correspond to different stages in the RID process. After determining the system layout, the team described the system layer's gaming elements. Figure 6 shows some of the outcomes.

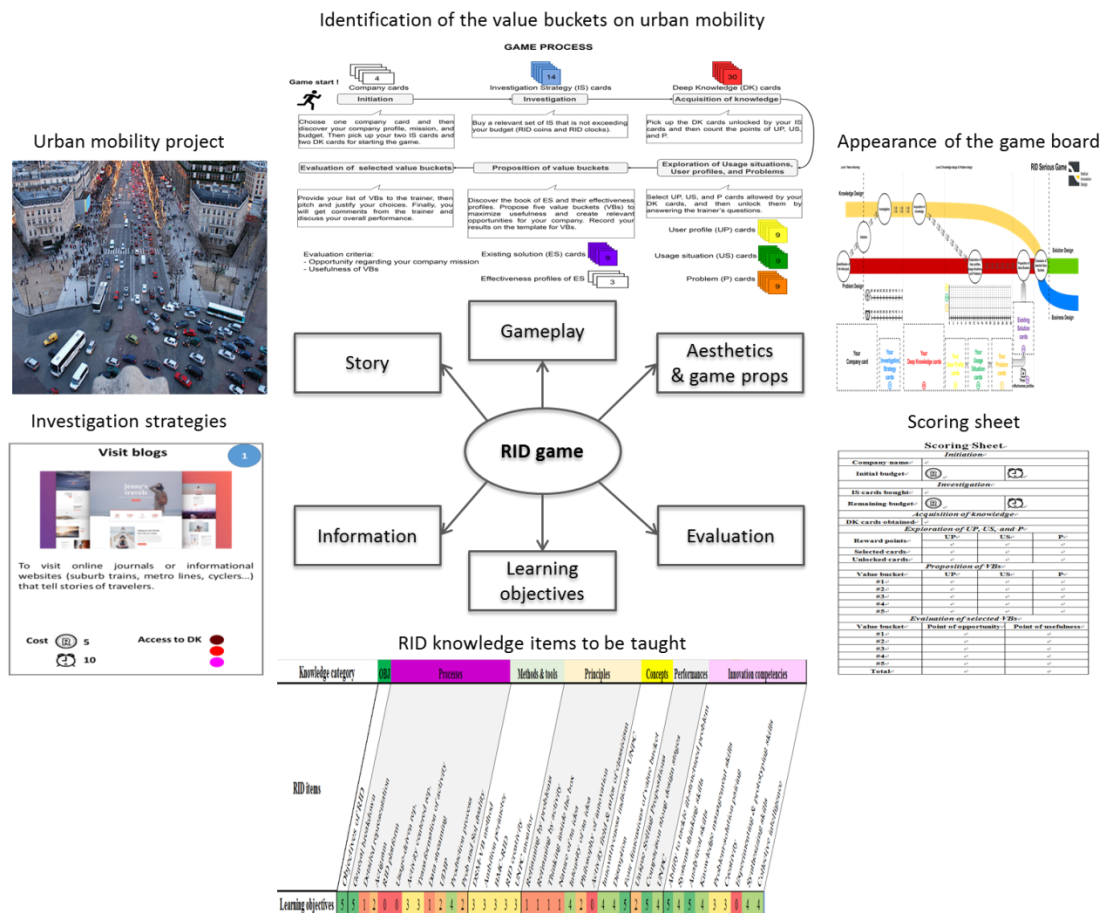


Figure 6. Gaming elements of the system layer

The description of gameplay, story, evaluation and information is gradually enriched as the design process proceeds. The game’s learning objectives are gradually decomposed and distributed into game levels. The same learning objective may be associated with multiple game levels. Due to time constraints, the design team only designed the third game level and its challenges based on the game system’s specifications.

The examples of the gaming elements of the RID game shown in Figure 7 were derived from relevant learning objectives. The gameplay of each challenge is inspired by the ‘RID actigram’ which defines all the activities to be performed to complete a RID project. RID principles had also been considered to describe the gameplay. To reflect the principle ‘thinking inside the box’ (Author, 2016), the trainer takes the role of project initiator and illustrates the original intention to launch a project on urban mobility. Players have to analyse the ultimate innovation objective of the project based on this initial idea. Six game challenges (numbered 1 to 6 in Figure 7) were imagined in order to articulate the fundamental RID concepts:

- Game challenge 1 invites players to pick a company;
- Game challenge 2 motivates players to invest their initial budget into relevant investigation strategies;
- Game challenge 3 provides players with knowledge cards and reward points for

user profiles, usage situations and problems;

- Game challenge 4 allows players to gain user profiles, usage situations and problems cards using their knowledge cards;
- Game challenge 5 encourages players to propose and evaluate value buckets;
- Game challenge 6 evaluates players' value buckets against Opportunity and Usefulness.

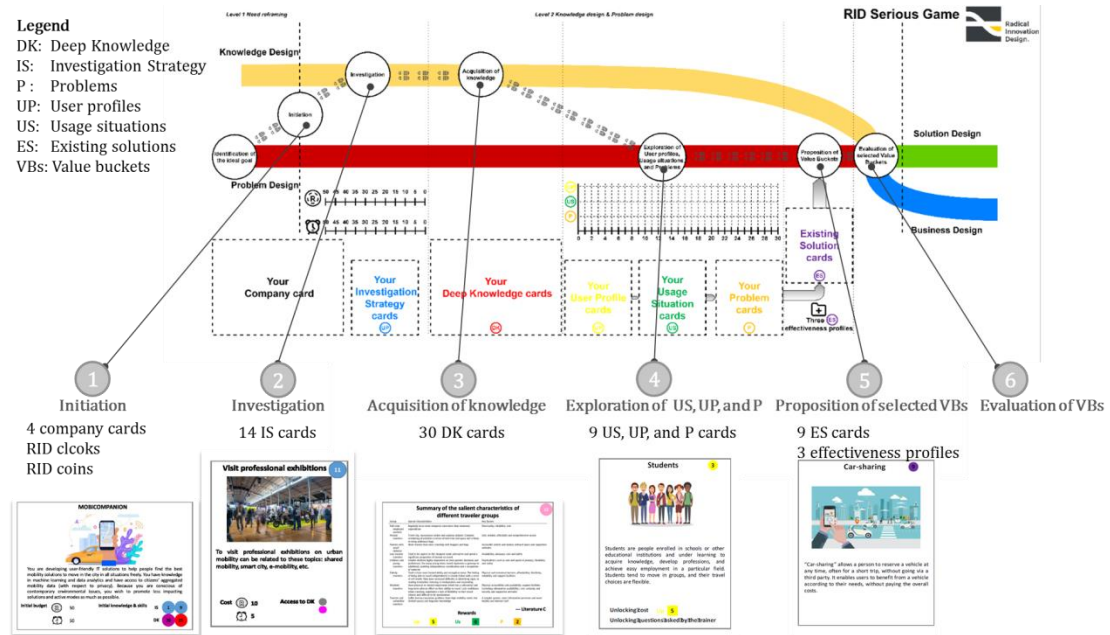


Figure 7. Gaming elements of the game level layer and game challenge layer

7. Verifying the learning experience

Before testing the game with players, teachers should act as verifiers to check whether the prototype achieves the learning objectives. The verification results can prompt designers to make improvements to the prototype.

The design team of the RID game first experienced the prototype and then created an ideal learning journey map for each game challenge (see Figure 8 for two examples). The ideal learning journey map describes players' expected actions and analyses what kinds of learning outcomes may be gained at certain intensity (see Table 4) by players if they perform the relevant actions. The map also examines the LM and GM contained in the gameplay based on the method proposed by Author (2019) to understand how the RID game creates a playful learning experience.

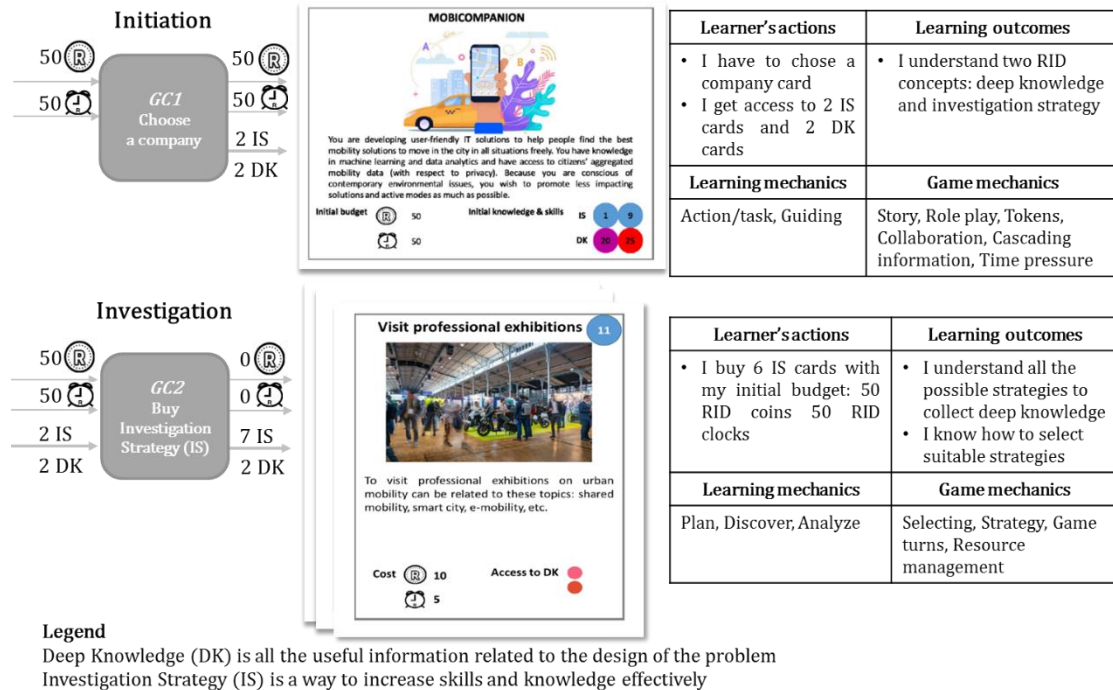


Figure 8. Ideal learning journey maps

When starting the ‘Initiation’ challenge, four players form a team and choose a company card. Each company has two attributes: an initial budget, which refers to the money (RID coin) and time (RID clock) that the company could spend, and an initial set of knowledge and skills that project-related. In the first challenge, players understand two crucial RID concepts. The second game challenge, ‘Investigation’, requires each team to use their budget to purchase suitable investigation strategy cards to gain more information about the project. By performing these actions, players could understand investigation strategies commonly used to develop ‘knowledge management skills’ and enhance their ‘collective intelligence.’

After creating ideal learning journey maps, teachers used a verification table to check each RID item’s intensity (from 0 to 5; see Table 4). The intensity of each item at a game level is the maximum value of the item’s intensity in all related challenges. Figure 9 sets out the intensity results and compares them with the specification of learning objectives in Figure 4. According to Figure 9, the Mean absolute error (MAE) of the intensities of RID items between the prescribed and realized learning objectives is 0.97. An MAE of 0.97 over a scale of 5 is already a fairly good result, but we only considered the contribution of game level 3 to the overall learning objectives for the game. Some learning objectives have not yet been fully achieved but will be addressed in the coming game levels. The verification table proves to be a convenient visual method to check that the realized SG appears to fulfil the prescribed learning objectives. As the intensity of most RID items is close to what teachers expected, it already partially proves the effectiveness of the four contributions of this paper.

| Knowledge category | OBJ | Processes | | | | | | | | | | Methods & tools | | | | Principles | | | | Concepts | | Performances | | | Innovation competencies | | | | | | | | | | | | | | | | | |
|----------------------------|-------------------|-------------------|-------------------------|----------|--------------|-------------------|------------------------|------------------------|----------------|------|--------------------|----------------------|---------------|--------------------|---------|----------------|--------------|-----------------------|-----------------------|-------------------------|-------------------|----------------------|-----------------------|------------------------------|--------------------------------|------------|---------------------------------|-----------------------------|---------------------------------|------|--|-------------------------|-------------------|----------------------|---------------------------|--------------------------|------------|------------------------------------|---------------------|-------------------------|---|---|
| RID items | Objectives of RID | General breakdown | Detailed representation | Actigram | RID platform | Usage-driven rep. | Activity centered rep. | Transformation of rep. | Data streaming | UDIP | Production process | Prob and Sol duality | DSM-VB method | Ambition perimeter | BMC-RID | RID creativity | UNPC monitor | Reframing by problems | Reframing by activity | Thinking inside the box | Nature of an idea | Intensity of an idea | Philosophy of an idea | Activity field of innovation | Innovativeness indicators UNPC | Disruption | Four dimensions of value bucket | Unique scaling Propositions | Comparison a long design stages | UNPC | Ability to tackle ill-structured problem | Systems thinking skills | Analytical skills | Knowledge management | Problem management skills | Problem-solution pairing | Creativity | Experimenting & prototyping skills | Synthesizing skills | Collective intelligence | | |
| Learning objectives | 5 | 5 | 1 | 2 | 0 | 0 | 3 | 3 | 1 | 2 | 4 | 2 | 3 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 | 4 | 2 | 0 | 4 | 4 | 5 | 2 | 5 | 4 | 5 | 4 | 5 | 4 | 3 | 3 | 0 | 4 | 4 | | | |
| Challenge 1 | 2 | | 1 | 1 | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | |
| Challenge 2 | 3 | 2 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 4 |
| Challenge 3 | 3 | 4 | 1 | 2 | | | 2 | 3 | | 1 | 4 | 1 | | | | | | 1 | | | | | | | | 4 | 2 | 1 | | 5 | 2 | 4 | 4 | | | | | | | | | |
| Challenge 4 | 4 | 4 | 1 | 2 | | | 4 | 3 | | 2 | 4 | 1 | | | | | | 1 | 1 | | | 1 | | | | 4 | 2 | 2 | | 5 | 4 | 4 | | | | | | | | | | 4 |
| Challenge 5 | 4 | 5 | 1 | 2 | | | 3 | 3 | 1 | 2 | 4 | 2 | 3 | 2 | | | | 1 | 1 | | 1 | 1 | | | | 1 | 4 | 2 | 2 | | 5 | 2 | 5 | 3 | 3 | | | | 2 | 4 | | |
| Challenge 6 | 4 | 5 | 1 | 2 | | | | | | 1 | 2 | | 3 | 3 | | | | 1 | 1 | | 1 | | | | | 1 | 5 | 2 | 2 | | 2 | | | | | | | | | | | |
| Level 3 | 4 | 5 | 1 | 2 | 0 | 0 | 4 | 3 | 1 | 2 | 4 | 2 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 5 | 2 | 2 | 0 | 5 | 2 | 5 | 4 | 3 | 0 | 0 | 2 | 4 | | | |

The expected intensity of each RID item of the entire game

The observed intensity of each RID item of each game challenge

The observed intensity of each RID item of game level 3

Figure 9. Verification table of game level

8. Validating the learning experience

The last stage of the co-design framework is validation. Teachers and game designers need to design and organize validation sessions to collect data used to evaluate the playful learning experience provided by the game. Finally, designers must continuously improve the prototype based on teachers' and players' feedback until all learning objectives are achieved.

Two methods were adopted to collect the data for validating the RID game: pre-test and post-test questionnaires and observation. The questionnaires were designed: a) to understand whether players' attitudes (SG's effectiveness and attractiveness) to serious gaming changed before and after experiencing the RID game; b) to find out whether they retain some RID-related knowledge; and c) to collect their feedback for improving the game.

The first part of the validation session aimed to introduce the schedule and objectives. The second part is a 2-hour game session. The last part is a debriefing session for players to voice their comments on the game. During the debriefing session, the trainer asked the players pre-prepared questions associated with validation objectives, such as 'what did you experience when playing the game?'

The design team set up similar questions in the pre-questionnaire and post-questionnaire to ask players to estimate the teaching effectiveness and playfulness of the RID game. Players' responses to the two questionnaires showed that the game provided a playful learning experience that exceeded their expectations.

The analysis of the post-questionnaire's results and the feedback given by the players in the sessions proves that the game effectively equips players with some essential RID knowledge items: 'existing solution', 'usage situation', 'value bucket', etc. Two beginners said that the RID game *changed their way of thinking out innovation processes*. As engineers, they used to think about solutions directly. However, after playing, they discovered how it could be beneficial to dedicate time to investigate and set the innovation problem by naming and prioritizing value buckets. They have grasped the characteristics of RID as a usage-driven and activity-centred innovation process that focuses on exploring users' problems and unstated needs.

The post-questionnaire sets out 14 statements to quantitatively evaluate the seven indicators of the gaming experience: immersion, flow, competence, positive affect, negative affect, tension, and challenge (Ijsselsteijn et al., 2013). The 23 players were asked to rate the extent (from 0–4) to which they agree with each statement, where 0 is strongly disagree and 4 is fully agree. Table 6 summarizes the relevant results.

Table 6. Evaluation of the gaming experience offered by the RID game

| Indicators | Statements | Mean |
|------------------------|---|------|
| Tension | I felt annoyed | 0.8 |
| | I felt frustrated | |
| Immersion | I was interested in the game's story | 2.9 |
| | It felt like a rich experience | |
| Flow | I lost track of time | 2.3 |
| | I was deeply concentrated in the game | |
| Competence | I felt skilled | 2.1 |
| | I was able to quickly achieve the game's targets | |
| Positive affect | I thought it was fun | 3.2 |
| | I enjoyed it | |
| Negative affect | I drifted away mentally to think about other things | 0.4 |
| | I felt bored | |
| Challenge | I felt challenged | 2.3 |
| | I had to put a lot of effort into it | |

The average score of the *tension* indicator was 0.8, which proves that players maintained a relaxed state of mind while experiencing the game. The only thing they found annoying was that the game session was too short. One player suggested extending the duration of the entire training session. For *immersion*, the score was 2.9, which indicates that the design team has plenty of room to further improve the plot of the story or introduce the story in a more immersive way (instead of oral presentation) to better foster situated learning. The average score for *flow* was 2.3. The players felt unable to totally engage in the game due to the 'time pressure' game mechanic. The six game challenges are different, and it takes time for players to master the gameplay, which makes it understandable that players did not feel *skilful* when playing. Players had an exciting gaming experience, as the average score of *positive affect* was 3.2. One player even stated that this as the best SG he had ever played. Mean score for *negative affect* was 0.4, shows that players enjoyed the game. Finally, the average score of the *challenge* indicator was 2.3. This difficulty setting keeps beginners motivated to play and to learn.

Based on player feedback given in the post-test questionnaire on the gaming experience, player motivation remained high when playing the game. They perceived the game as well-designed, which is in line with our observations of players' facial expressions and their level of engagement. The RID game achieved its learning objectives, but still demands further improvements based on players' valuably helpful suggestions.

9. Discussion and Conclusions

The work reported here aims to facilitate collaboration between IE teachers and game designers in SG design without forcing them to acquire too much of each other's expertise. A co-design framework is proposed to answer the research questions by

clarifying the division of tasks between teachers and game designers. To optimize task efficiency, each design-team member is only responsible for the tasks they are skilled for (Table 7).

Table 7. Design tasks of teachers and game designers in the co-design framework

| Stakeholder | IE Teacher | Game designer |
|--|--|---|
| Design stage | | |
| Decomposition of the IE methodology | <ul style="list-style-type: none"> Gather and organize as much knowledge as possible about the targeted IE methodology. | - |
| Specification of learning objectives and gaming experience | <ul style="list-style-type: none"> Choose the knowledge items that want to teach in the game and determine their intensity grade. Transcribing learning objectives represented by the specification vector into text | <ul style="list-style-type: none"> Communicate with teachers to fully understand learning objectives Communicate with the teacher to specify the expected gaming experience |
| Design of gaming elements | <ul style="list-style-type: none"> Assess the pedagogical effectiveness of game ideas based on teaching experience | <ul style="list-style-type: none"> Generate game ideas for realizing all the learning objectives Improve game ideas based on teachers' feedback Develop the game prototype |
| Verification of the learning experience | <ul style="list-style-type: none"> Verify the learning experience | <ul style="list-style-type: none"> Verify the gaming experience |
| Validation of the learning experience | <ul style="list-style-type: none"> Design and organize the validation session Gather the data for validating the game Summarize the suggestions for improving the game | <ul style="list-style-type: none"> Design and organize the validation session Improve the game design |

Four tools are then provided to support them in completing all the tasks in Table 7. The first tool is a *domain decomposition model*, which helps teachers create a repository to

store and organize all the relevant knowledge items of a given IE methodology. The model was developed by summarizing the teaching content of 12 representatives of IE methodologies, and its validity has been confirmed by 15 randomly selected but relevant educational experts. Second, teachers are provided with a *specification vector* to help comprehensively describe the game's learning objectives based on measurable verbs so designers can quickly and easily understand. The IE methodology items thus become like objects on shelves. In this way, teachers and designers can establish a common understanding of how to formulate and express the learning objectives. The vector allows teachers to consider the importance of each knowledge item separately from the perspective of different categories of IE game audiences and then to set comprehensive and reasonable learning objectives. It was successfully used to specify learning objectives for the RID game, and its external validity needs further validation. Although teachers are not necessarily involved in creating gaming elements, they may need to evaluate the effectiveness of some preliminary ideas generated by designers or to choose from several game ideas. Thus, the *design language model of SGs* helps them develop a basic understanding of the general architecture of SGs. Furthermore, if designers can use the same language, it will be easier for them to discuss game ideas with teachers. The design language model completes the acknowledged SGDA framework, and new design objects can be easily identified from existing IE games, ensuring its internal and external validity. A *map between the domain decomposition categories and gaming elements* is offered to guide designers in generating game ideas based on the learning objectives. The relationships between these two contributions depicted in this map are consistent with the experiences of four senior IE game design professionals, which is initial proof of its validity (Author, 2021). The map is exemplified based on the RID game, which helps IE teachers understand the educational content contained in the game ideas submitted by designers. It will be used to inspire the design of other IE games to assess its generalizability further. The last tool is a *verification table* to check whether the learning experience is aligned with the game's learning objectives. Teachers use the same specification vector when setting learning goals and verifying the game, which further helps to simplify their tasks. These contributions enable teachers and designers to complete their respective tasks in the SG design process and exchange their thoughts fluently.

To prove the validity of this research, all propositions are further exemplified based on the design experience of the Radical Innovation Design game. The design team organized three validation sessions with 23 players (with or without RID prior knowledge) and adopted a pre-test and post-test approach to capture feedback on the learning experience. To explore the actual learning experience that the game offers, players were selected based on the characteristics of the designated audience, and the flow of each session was set according to the expected usage scenario of the game. Analysis of the testimony and answers to these questionnaires proved that the game equips players with some important RID concepts in a fun way. It also spurred their motivation to further RID practices. The players perceived the game as well-designed and felt it presented the different stages of the RID process in a structured way. This

validation of the RID game contributes, at least partially, to validate the relevance of the SG co-design process proposed in this paper.

Unlike other relevant studies in the SG domain, the co-design process introduced in this paper does not oblige teachers to participate too much in the game design and implementation stages. It emphasizes that the design-team members need to be left to complete the tasks they are good at. Teachers need to set precise learning objectives and verify and validate the prototypes with designers, while designers need to generate and implement appropriate game ideas. It remains possible to involve teachers in some creativity sessions. We anticipate that these contributions as a start point to help facilitate and liberate the design of SGs.

The authors have played three roles in this study: inventors of the RID methodology, the proposer of the co-design framework, and designers of the RID game. However, this particularity does not affect the applicability of the contributions. First, seven experts on 12 IE methodologies validated the usability and understandability of the proposed domain decomposition model, and its usefulness in defining learning objectives was then assessed by eight other experts (Author, 2021). Based on the analysis of the validation results, IE teachers do not find it hard to apply the model to define the learning objectives of SGs. Second, the teachers' main task in the co-design process is not to generate game ideas but to specify the learning objectives and validate that a resulting SG achieves these stated objectives. They only need to understand the structure and composition of SGs in order to be able to communicate with game designers when necessary. The design language model introduced in Section 3 provides all this knowledge. Third, in Author (2021), the mapping table between domain decomposition categories and gaming elements was also applied to imagine a SG on the Life Cycle Assessment (LCA) methodology. For these three reasons, it is entirely feasible for teachers to collaborate with game designers and follow the proposed co-design process to create SGs for teaching whatever IE methodologies they want to teach.

Future research work will focus on two aspects. First, making teachers and game designers responsible for the tasks they are good at is expected to increase the design team's efficiency. Even if this is a solution that could encourage reluctant teachers to embark on the adventure of creating a SG, there is still a lack of evidence to prove that such an approach is more efficient than—or at least as efficient as—other approaches that aim to get teachers more involved in the design tasks. We need to invite teachers and game designers to further test the proposed co-design process and collect their feedback on its effectiveness and efficiency. Second, the intention of the mapping model is essentially similar to the Design Pattern Library proposed by Marne et al. (2012a), as these two studies all aim to provide examples and guidance for the design of SG elements. The mapping model could be further developed by introducing the design ideas of gaming elements of different IE games, like the RID game discussed here, which could provide IE teachers and game designers with richer inspiration for SG design.

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