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Serious games for industrial safety: an approach for developing resilience early warning indicators

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Abstract

The development of safety indicators represents an integral part of any safety management process. Safety indicators are generally classified as leading or lagging, respectively whether they are active (providing feedback on performance before an accident or incident), or reactive measurements (identifying and reporting on incidents to identify weaknesses and failures). Leading indicators have been largely addressed as early warning instruments crucial to assess the potential for either safety events (accidents, incidents), or system's resilience. The Resilience-based Early Warning Indicator (REWI) method is a representative approach to develop such indicators. However, its main challenges are related to the data gathering process, which is traditionally managed by open-ended interviews or surveys, and the fact that the developed indicators may not necessarily represent proxy measures of system performance. This paper presents an alternative methodological framework for the development of leading indicators. We will explore the use of GREWI (Games for Resilience-based Early Warning Indicator method), a new method based on gamified data gathering, more specifically related to serious games. Abandoning traditional tick-box surveys, the proposed approach is intended to favour workers' engagement in workplace safety and, more in general, to overcome psychological barriers to their participation. The approach has been explored in a case study within chemical industry. In particular, the safety-critical sector of ammonia production has been addressed, with the purpose to promote and improve its resilience towards unwanted events.

Keywords

Industrial safety; safety indicators; resilience indicators; serious games; socio-technical systems.

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1. Introduction

The promotion of healthy working conditions is essential for ensuring both productivity and overall socioeconomic sustainability. The purpose of risk management mainly consists of: i) anticipating and recognizing risks and their causes, ii) assessing the identified risks by taking advantage of relevant data, and iii) setting recommendations and corrective measures (if any) to eliminate or eventually mitigate the effect of risks themselves (ISO-International standardization organization, 2009). Over the last decades, many methods and models have been developed for supporting these risk-oriented tasks and activities (Harms-Ringdahl, 2013), generally starting from a pure techno-centric perspective, considering then human factor, and then organizational factors (Hollnagel, 2014). The continuous evolving nature of work in modern societies implies the need to reconsider the notion of risk and safety, and consequently to change the way risks and safety are modelled and interpreted within different industrial fields (Rum et al., 2018). Current work domains envisage dramatic technological changes, and the subsequent increasing complexity of products and processes calls for approaches which acknowledge the inherent complexity of systems, adopting a holistic perspective (Wilday et al., 2011). This perspective demands for abandoning traditional Newtonian notions (e.g. "human error", "organizational failure", "complacency"), consequently shifting the focus from what has happened - often being trapped in constructivism (Wrigstad et al., 2017) - to reveal the source of success when failure threatens, i.e. the source of resilience. A resilience-oriented perspective acknowledges that safety analyses focused only on adverse events (e.g., counting the number of failures, casualties, injuries, etc.) may hinder a complete understanding of the process, in light of a zero harm vision (Dekker et al., 2016; Grøtan and Paltrinieri, 2016; Paltrinieri and Khan, 2016). These statistics often provide an illusion of understanding the reality, supporting the analyst's - and decision-maker's - anxiety about complexity and non-linearity. However, they do not support an in-depth understanding of how sharp-end operators work, disregarding how trade-offs are balanced and achieved in real operating conditions. Such statistics often lead to difficulties in predicting unexpected events, shifting to bureaucratic accountability (Hale et al., 2013), and ''numbers games'' (Creedy, 2011; Dekker, 2014).

This paper embraces a resilience-oriented perspective (Woods and Hollnagel, 2006), proposing to develop a set of performance indicators which could represent early warning signals of system functional criticalities. Starting from the guidelines suggested by the Resilience Early Warning Indicator (REWI) method (Øien et al., 2010) and their applications (Paltrinieri et al., 2012a, 2012b, 2012c), the paper describes the process of defining a set of process safety indicators for complex socio-technical systems. Such process overcomes traditional methods to gather data about OHS risks based only on tools (Oliveira et al., 2018; Patriarca et al., 2017;

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Podgórski, 2015) such as checklists and questionnaires, which do not necessarily address participants' engagement. Starting from the widely discussed benefits of gamification (Sailer et al., 2017), this paper explores the potential usage of game-based approaches to motivate operators' engagement in safety management processes through serious games. A common criticism is related to the attitude of the workers in participating in gamified experiences. However contemporary workers are less prone to this issue as they are often accustomed to video games (e.g., massively multiplayer online role-playing game) and using game elements in serious contexts (Malhotra et al., 2017; Reeves and Read, 2009).

In summary, this paper aims to propose a methodological contribution to answer the following research question: "How should serious games be developed to define early-warning indicators for industrial safety?" In particular, we propose the GREWI (Games for Resilience-based Early Warning Indicator) method to answer such question. The notion "indicator" refers to the intention of adopting a perspective that may help the operators and the analysts in understanding the complexity of system performance, rather than just having metrics on the number of adverse events. Even if the term "should" refer to the normative dimension of this research (cf. "how things should be"), we want to emphasize that the methodological contribution proposed in this research is not rigidly prescribed, but rather customizable based on the specific system being investigated.

The remainder of the paper is organized as follows. Section 2 reviews relevant literature about indicators for safety management, summarizing their different dimensions. Section 3 outlines the principles and basic steps of the REWI method. Section 4 describes the methodological process proposed in the research for the development of early warning indicators. Section 5 presents the case study of an ammonia production system, as a walk-through application to provide insights on the application of the proposed gamified approach. Section 6 emphasizes strengths and weaknesses of the approach. Lastly, the Conclusions summarize the outcome of the research and pave the way to further research. The three Appendixes complement the methodological discussion, with in depth details of some methodological aspects.

2. About indicators

A reliable monitoring framework represents an essential aspect for effective safety management on different organizational levels. In particular, long-term management follows the company's vision, which is usually translated into assessing a number of operational performance indicators at the middle-management level, to be summarized for the executive level in dashboards mainly highlighting

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relevant deviations and trends. It becomes thus necessary to focus on a meaningful set of indicators which is - or at least, is supposed to be - able to depict system performance and to support the generation of meaningful hindsight. Such reactive approach is strongly rooted in Western culture, and basically considers counting adverse events (Hollnagel, 2012). Safety is thus measured by its absence: the higher the number of adverse events, the lower the safety level (Di Gravio et al., 2016). Safety, especially regarding modern complex systems cannot restrict itself within a reactive approach but needs proactivity, which cannot rely only on information gained *ex post* from experience (Paltrinieri and Khan, 2016; Scarponi et al., 2016; Scarponi and Paltrinieri, 2016; Woods, 2011).
About the timing for information gathering, the distinction between leading and lagging is born mainly to specify the different moments in which the usage of the indicator may support gaining information about the system's state. The earlier the indicator supports gathering system state's information, the larger will be the margins of manoeuvre, prior to outcome of the system (either negative or positive). Proactivity arises in obtaining this operational margin.

The distinction between leading (proactive) and lagging (reactive) indicators, and the respective lexicon, originates in economy, see (e.g.) (Moore, 1969). In terms of safety management, one of the first usage of this distinction dates back to the Baker Report (Baker et al., 2007), as further debated following a theoretical perspective (Hopkins, 2009). In order to delve in-depth in the analysis of the leading/lagging indicators, it is helpful focusing on the notion of indicator itself. Formally, an indicator is “a thing that indicates the state or level of something” (cf. Oxford dictionary, 2018). Nevertheless, especially in complex socio-technical systems, accessible quantities that can be measured easily do not necessarily provide meaningful insights about what really concerns the system state proactively (Lundberg et al., 2009).

Similar concerns arise when categorising safety indicators (regardless of their leading/lagging dimension) as personal or process ones (Baker et al., 2007). Personal (or occupational) safety indicators affect individuals and are mostly related with personal safety hazards. On the contrary, process (or asset or technical) safety indicators refer to issues arising from the scenario in which the entire organization is engaged. Both these dimensions traditionally refer to injuries and fatality statistics, which have been proved to be ineffective for a complete and holistic assessment of organizational safety (Hopkins, 2009).

Based on these observations and following the literature in the field, this research considers an indicator to be leading if it forewarns the analyst about potentially different actions to be undertaken in order to grasp an opportunity or to evade a threat. Otherwise, an indicator is considered to be lagging if it allows acknowledging deviances from expected outcomes in occurred events, being they favourable or not. It has to be observed that this conceptual distinction has been widely accepted in theory, even as a means to explore the epistemic nature of the control problem (Le Coze, 2009).

A critical aspect of adopting safety indicators is related to their potential manipulation in case a corporate safety culture is not firmly established. In this scenario, the focus on "what can be measured" overcomes "what should be measured" - or worse, it follows misleading objectives "what interests my boss fascinates me!" (Webb, 2009) - critically affecting the understanding and management of systems' states (Cabrera Aguilera et al., 2016; Erikson, 2009; Glendon, 2009; Hudson, 2009). An important lesson learnt from this debate is the need to adopt a dynamic and agile methodology to continuously identify and refine the most appropriate indicators within the safety culture under examination (Bellamy, 2009; Hale, 2009; Paltrinieri et al., 2016; Paltrinieri and Khan, 2016; Webb, 2009), rather than proposing unmotivated efforts in labelling indicators as leading or lagging (Wreathall, 2009).

Since the early Resilience Engineering documents (Dekker, 2006), it is acknowledged that the observational interest should be focused on performance variability, intended to be the source of both success and failure (Patriarca et al., 2018; Righi et al., 2015). For these reasons, referring exclusively to traditional bad-outcome indicators (e.g. accident/incident/failure count) may be misleading. Oppositely, it should be remarked that leading and lagging indicators are rather defined as means to provide information on both good and negative events, i.e. on system's capability to ensure normal behaviour before, during, and after an internal or external perturbation (Hollnagel, 2014).

Based on these observations, this research proposes a methodological framework to develop outcome-based and activity-based domain-specific indicators, which can be dynamically assessed, refined and - possibly - updated by means of serious games. In practice, the perspective embraced in this study follows the REWI method and redesign it through the usage of serious games. It is important to observe that the resilience-oriented perspective in the REWI, as well, as in the proposed GREWI, focuses more on the social than technical aspects of the system at hand.

3. The REWI method

This research follows a resilient pragmatic perspective based on the REWI method, i.e. a systematic approach for proposing, developing and validating early indicators of resilient performance in socio-technical systems (Øien, 2016; Øien et al., 2010). A similar notion of "early-warning" signals has been used also in biology (Gsell et al., 2016). As stated in the method guideline (Øien et al., 2012), the REWI envisages an operationalization of Resilience Engineering, through a progressive specification of the elements that may allow resilient performance in a socio-technical system. At the first hierarchical level (Level 1), the REWI method assumes

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resilience as expressible by three so-called (overall) Contributing Success Factors (CSFs): (1) Risk awareness; (2) Response capacity; (3) Support. At Level 2, each overall CSF is specified into a set of corresponding (detailed) CSFs for a total of eight factors:

- (1) Risk awareness: 1.1 Risk understanding; 1.2 Anticipation; 1.3 Attention.
- (2) Risk understanding: 2.1 Response (including improvisation); 2.2 Robustness (of response); 2.3 Resourcefulness/rapidity;
- (3) Support: 3.1 Decision support; 3.2 Redundancy (for support).

Exploring the lower hierarchical level, each detailed CSF is then specified into General Issues (GIs), for overall 38 GIs. The last level specifies each GI into a set of operational indicators, for overall 147 REWIs. The hierarchical structure is represented as follows: a dot in the notation represents a level, while the numbers refer respectively to the coded overall CSF, detailed CSF, GI, and REWI. For example, 1.1.1.1 "Average no. of years' experience with such systems" is a REWI that specifies resilience through overall CSF 1 ("Risk awareness"); detailed CSF 1.1 ("Risk understanding"); and GI 1.1.2 ("System knowledge").

As noted by the authors themselves, the REWI framework should not be rigidly interpreted: it is intended as a means to provide a preliminary set of metrics that serve as a starting point for continuous assessment. The actual strength of the method lies in promoting a collective sense-making of how system performance can be measured, focusing on adaptation and response, in line with recent approaches for safety management. Operationally, the REWI method is implemented in five main steps (Øien et al., 2012):

1. Establish the organizational arrangements necessary to set up the various stages (e.g. organize the implementation and assessment team; identify the different stakeholders involved).
2. Starting from the default REWIs, identify and select relevant indicators REWIs; eventually add or prune hierarchical levels and adjust the respective width (i.e. numbers of items for each level); finally select the most manageable subset of indicators.
3. Implement the chosen set of REWIs and interpret data.
4. Review and update regularly the chosen set of REWIs and evaluate the need for changes.
5. Integrate the REWIs with other self-assessment initiatives, if necessary.

About steps 1 and 2, this research confirms the REWI emphasis on social engagement, for disseminating concepts within the organization. This dissemination aims at sharing a common language to collaboratively disclose information about everyday work, with no fear for blaming consequences.

Nevertheless, even if the core idea of REWI relies on recent safety thinking (cf. Resilience Engineering, Safety-II), and thus on exploring the factors contributing to success (CSFs) by means of early warning indicators, the method itself presents some potential criticalities. The REWI detailed hierarchical decomposition may imply the definition of indicators which are not necessarily early warning signals. For example, about the REWI "1.1.1.4 Average no. of hours system training last 3 months" not necessarily represent a proxy measure of the respective GI "1.1.1 System knowledge" (the training could be inappropriate, or not necessarily well-received by the trainee). Or similarly, the REWI "1.1.1.6 "No. of violations to authorized entrance of systems" has an inherent lagging dimension, not necessarily including an early warning proactive perspective. These indicators seem to reflect the controversial criticality about "What can be measured" vs "What should be measured", already mentioned in §2 (Webb, 2009). Furthermore, other items at the fourth level of the hierarchy may be difficult to interpret and properly define, (e.g.) GI "1.2.2 Learn from own experiences & accidents", or "1.2.3 Learn from other's experience & accidents", as confirmed by the method guidelines, where the respective REWIs are in both cases "On hold".

On these observations, this research does not follow the four-level hierarchy of traditional REWI method, but rather focus on the definition of eight detailed CSFs (at the second level of the REWI hierarchy), i.e. the actual factors contributing to the system's success. The research proposes gaming as the common language to engage system operators in safety management, and contemporarily gather relevant meaningful data, and limit the biases of traditional audits. A game-based approach would thus strongly support step 3 of the method, directly involving the game participants in the implementation of the new leading indicators. It would also support step 4, providing the basis for a continuous data gathering and data updating.

4. The Games for Resilience-based Early Warning Indicator method (GREWI)

The aim of this section is to present the GREWI, a new method to develop REWI indicators by means of a gamified approach. The GREWI has to be intended as guidance for an analyst to define new engaging gamified activities, starting from ad hoc canvas to be adapted and completed for specific application needs.

4.1. Relevance of serious games

In recent years, there has been a growing research and industrial interest in transferring game elements to non-game contexts (Baptista and Oliveira, 2018). The original motivation of this interest mainly refers to the social dimension of a game, i.e. increase the engagement of employees in a business process (Sailer et al., 2017). A well-designed game can engage and excite the player, who, playing, commonly experiences feelings that are characteristics of intrinsically motivated human behaviours (e.g. mastery, competence, enjoyment, immersion, flow) (Koivisto and Hamari, 2019). Traditional information gathering processes through questionnaires and/or workshops generally feature low participation and engagement of the responders, hindering the potential for credible information. In this context, utilitarian games, both in terms of gamification and serious games, are an intriguing combination of both utilitarian and hedonic systems: the goals of the systems are oriented at productivity, through means that are hedonic in nature (Hamari and Keronen, 2017). Utilitarianism and hedonism have thus to be properly balanced for a game development (Deterding et al., 2011). Such combinations have been largely implemented in a large set of domains, among others: education, crowdsourcing, data-collection, health, social network, and environmental protection (Sailer et al., 2017). A particular type of utilitarian games is represented by the serious games, which differently from gamification, are fully-developed games serving a specific non-entertainment purpose. As such, it is acknowledged that the serious game development team shall involve instructional scientists and subject matter experts of the utilitarian domain to be inspected (Zyda, 2005). Despite the largely discussed benefits of serious games (Boyle et al., 2016), conceptually, and particularly in the safety science domain (see e.g., (Bellamy et al., 2018; Bellotti et al., 2010; Chittaro and Buttussi, 2015)), there is no specific framework approach for their developments, and often the research is devoted only to specific case studies (Charsky, 2010). Based on these observations, we aim to define a methodological contribution overcoming the limitations of traditional data collection strategies (Sailer et al., 2017), through a framework for supporting the development of utilitarian and hedonic games in the context of resilience engineering.

4.2. Description of the gamified approach to gather REWI indicator values

Figure 1 sketchily presents the gamified approach compared to the traditional one, clarifying that the GREWI envisages a decluttered perspective on resilience, restricting its focus at the Level 2 CSFs, rather than at the specific REWI indicators. The GREWI proposes a CSF canvas (i.e. GREWI canvas). This latter is a conceptual framework to be used as an abstract blueprint to track the entire GREWI development process, including game design and performance indicators. The GREWI is intended to be a support tool at operational level to support the game implementation. This method is detailed in 7 steps, which are led by the GREWI analyst, who is the person in charge of the gamified activity in the organization. He/she should have a background in safety management, and ideally some notions of gamification. In the following section, the GREWI analyst may be used as a reference to a pool of analysts with complementary backgrounds for better arranging the game management process.

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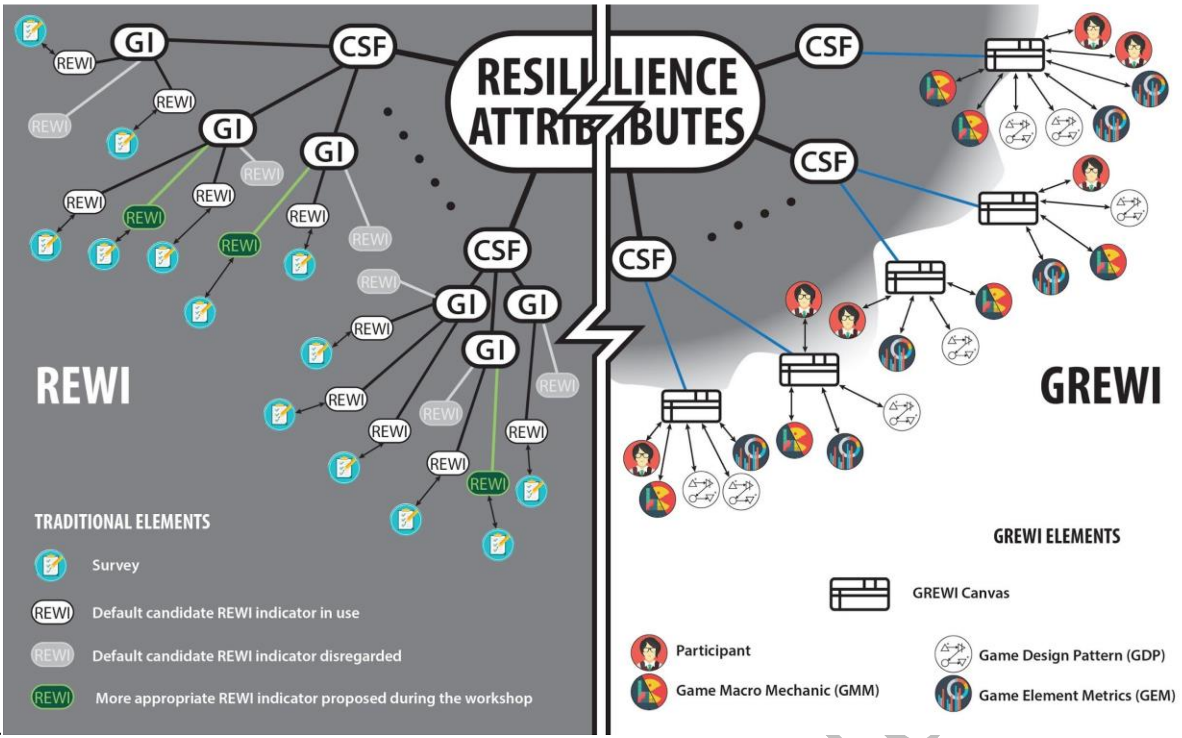

Figure 1. Representation of the serious games approach for REWI information gathering.

Step 1. Definition of the scope of the analysis. The GREWI analyst has to define the application context for the analysis (which process/sub-process, resource involved, etc.). This step refers to REWI step 1, but differently from traditional REWI, in GREWI, organizational arrangements for the analysis are not required yet.

Step 2. Identification of Contributing Success Factors (CSFs). The GREWI analyst identifies the CSFs and, hence, the detailed CSFs that should be coherent with the scope of the analysis (Øien et al., 2012). This step is compliant with REWI step 2, except for the granularity level of the items to be inspected. The actual indicators will be defined after the definition of the gamified activities.

Step 3. Completion of the GREWI canvas. The GREWI analyst fills in a GREWI canvas, with the purpose of specifying the main features of the specific game. The GREWI canvas follows a structure and purpose similar to that presented in (Coletti et al., 2017). The canvas allows specifying the relationships between: i) the selected detailed CSF and game mechanics; ii) the game mechanics and the game design patterns; iii) the game design patterns and the actual game to be developed; and iv) the game and the game metrics (which will constitute the proxy indicators of resilience). The GREWI canvas constitutes the core element of the process and its completion step is composed of 4 sub-steps, which inherently include also the organizational arrangement for the analysis.

a. **Prioritization of Game Macro Mechanics (GMMs).** For each CSFs, the GREWI analyst should select firstly the most appropriate Game Macro Mechanics for its representation in the game (Adams and Dormans, 2012).

A GMM is an abstract concept that summarizes the underlying rules, process and data at the heart of a game: it defines the actions and evolution of the game as well as the victory and defeat conditions. It has been acknowledged that five GMMs properly summarized the main game concepts:

- *Physics.* This GMM refers to the science of matter, energy and their interaction. Mainly motion and force in general are the most representative physics items in a game, which could adopt them at different detail levels, ranging from ultrarealistic simulation games to physics-puzzle games.
- *Progression mechanisms.* This GMM is about the definition of the game evolution, i.e. defining how progresses through the game should be implemented, by which logic and mechanisms.
- *Tactical manoeuvring.* This GMM refers to the design of strategic advantages as a consequence of particular decisions taken (and actions performed) by the game player. These advantages could be both (possibly jointly) local, i.e. providing short-term consequences, or global, i.e. affecting long-term scenarios.
- *Social interaction.* This GMM refers to the design of game actions related to interaction among game players, (e.g.) reward giving gifts, inviting friends, collaborating for succeeding with missions.
- *Internal economy.* This GMM refers to any type of quantifiable transactions involving the previous GMMs. In operational terms, this GMM refers to the design of quantifiable items related to physical, progression, tactical, social mechanics. Internal economy is usually a crucial mechanics to define victory and defeat conditions.

The association between Level 2 CSFs and GMMs should be based *Table 2*. This latter has been built following a survey conducted by 5 SMEs with experience in game design, risk and resilience management (further details in Appendix 1).

b. **Preliminary selection of game design patterns (GDPs)**. A GDP is a documented and objective solution to a common game design problem. Following previous literature in architecture (Alexander et al., 1977) and software engineering (Gamma et al., 1995), GDPs provide a common vocabulary for game designers and inherently support the development of high quality games. The GREWI analyst associates each GMM to one or more GDPs, following Table 3, which has been based on (Adams and Dormans, 2012). A complete list of GDPs is presented in Appendix 2, following (Adams and Dormans, 2012).

c. **Definition of gamified activities.** Based on the identified GDPs, the GREWI analysts should develop the game activities by providing a narrative of the game specification, in relation to the relevant GDPs, possibly by an iterative

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approach. It could be helpful at this stage to be inspired by previously developed games in order to find a proper concrete conversion of the suggested GDP in actual elements of the game, which remain meaningful for the scope identified in Step 1 (see e.g. (Adams and Dormans, 2012)). Note as well, that during the game definition, the GREWI analyst has to take into account who will be the game player, i.e. who will be the source of information for the specific CSF. Ideally, depending on the player, the GREWI analysts should implement the GDPs in a different game type (role playing game, arcade, puzzle game, simulation, etc.) which could be more suitable for his/her participation. Even though it has been widely discussed in literature that different type of persons would prefer some types of game to others (cf. e.g. Bartle's taxonomy (Bartle, 1996; Hamdaoui, Khalidi Idrissi, & Bennani, 2018)), it has been observed that role playing games and simulations are generally the most helpful techniques for representing issues related to socio-technical systems, as successfully proved in ad hoc case studies on the usage of serious games for resilience (Bellamy et al., 2018; Cedrini et al., 2018).

d. **Definition of game element metrics (GEMs).** The GREWI analyst should customize the GEMs to be adopted and appropriately designed as part of the game itself. A GEM is a metric which helps assessing performance during -or after- the proposed game. Following the structured transferral process of system properties into the game design process, a GEM ultimately represents a proxy measure of the selected CSF. It could be observed that GEMs are usually helpful to define a relative representation of the system state through player performance, rather than absolute measures. Note that main GEMs refer to the assessment of the player performance ("Individual score", "Team Score", "Team building", "Duration", "Respect for the rules", ""), but there could be worth to define other GEMs for the purpose of the game assessment ("Feedback on the gamified experience"), constituting a constructive feedback for game refinement. At this stage, the GREWI analyst customizes the general GEMs to make sense for the game he/she developed.

Figure 2 summarizes the "GREWI routes" which is a synthetic representation of the proposed steps to develop the GREWI canvas.

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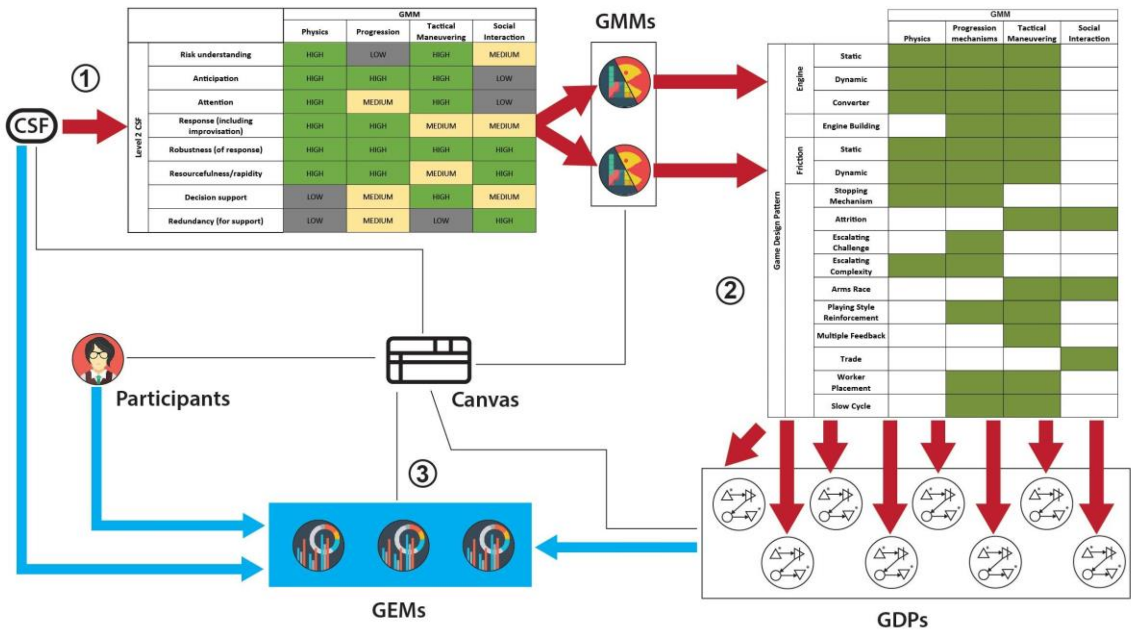

Figure 2. The process to complete a GREWI canvas consists of three main steps: Step 1) Table 2 outputs prioritizes GMMs for a certain Level 2 CSF. Step 2) Similarly, Table 3 connects GMMs and GDPs. Generally, these two steps will produce multiple outputs that in the diagram are schematized with red arrows. In our case, from the given Level 2 CSF (Response incl. improvisation), the red route begets two GMMs and eight GDPs, both used to fill in the canvas. Step 3) Definition of the GEMs. The GEMs, to be significative, should consider both the Level 2 CSF information and a number of participants for the information, starting from the previously obtained GDPs (the blue route). Table 2 and Table 3 are detailed in the appendices.

Step 4. Implementation of gamified activities. The GREWI analyst sets up and implements the gamified activities based on the GREWI canvas, with particular care to the GDPs and the GEMs. It is recommended to run test experiments with a reduced pool of players before submitting it to the entire organization. It would even be preferential to construct a simulator model of the proposed GDPs (or at least the more relevant ones), to check their consistency and significance, as well as to obtain credible estimations of the game duration and scoring. In the context of game design, such simulation models refer to the notion of machinations (Adams and Dormans, 2012), which are developed on the basis of the available GDPs. At this step, it becomes necessary to arrange the organizational process of data gathering, considering if the proposed game belongs to IT category or the board game category.

Step 5. Analysis of game results. Using the GEMs values obtained through the gameplay, the GREWI analyst has to assess the individual and system performance, and consequently, derive implications for proxy measure of the proposed CSF. The step conceptually refers to REWI step 4, enhancing it through a bottom-up gamified approach.

Step 6. Review of GREWI attributes. The GREWI analyst reviews and updates regularly the chosen set of GDPs and GEMs (i.e. the game) based on the specific context and/or intermediate results. The revision process should follow a cost-effective balance, prioritizing the revision of the GEMs, rather than the one of the GDPs. At this step, the GREWI canvas constitutes a tool to support

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organizational sense-making and to provide objective data on previous experience, with the ultimate goal of guiding a progressively enhanced game experience.

Step 7. Integration with other self-assessment initiatives (optional). Depending on the specific context and if necessary, the GREWI analyst may integrate the gamified activities with other self-assessment initiatives, e.g., other data gathering process, audit information, training actions to confirm, revise and increase the results obtained through the GREWI actions. The step conceptually refers to traditional REWI step 5 (cf. §3).

5. A walkthrough application: ensuring successful plant emergency response in case of ammonia release

5.1. Description of the scenario

The conceptual framework described in §4 has been explored and hereafter contextualized in a high-risk socio-technical system: an ammonia production site. Ammonia plays a key role in the manufacturing of many chemical industry products. It is not only used for fertilizers (which employs up to 85% of ammonia production), but it also represents a building block for plastics, pharmaceutical and explosives (Moulijn et al., 2013). However, this substance in its gaseous state is flammable and highly toxic for humans (Afrox, 2015), and its handling presents important criticalities despite being a consolidated chemical process. For this reason, anhydrous ammonia is listed among the dangerous substances regulated by the so-called Seveso directives on the control of major-accident hazards involving dangerous substances (European Parliament and Council, 2012).

Historically, the steam reformer and ammonia synthesis reactor have been the most affected by failures and releases within the ammonia production process, due to their extreme operational conditions (high pressure and temperature) and the substances treated in addition to ammonia (e.g. natural gas or hydrogen) (Ojha and Dhiman, 2010). Other issues may lead to unexpected releases in the plant, such as corrosion in the sour gas removal section, high temperature hydrogen attack leading to loss of mechanical properties of the methanation reactor, or brittle fractures of the cryogenic storage vessels (Ojha and Dhiman, 2010).

5.2. Methodological walkthrough

Step 1. We suggest the evacuation scenario in an ammonia production plant as a potential walkthrough application example for the GREWI. As in most of the plants dealing with hazardous substances, the evacuation procedure in case of ammonia release is paramount, because it represents one of the last available measures mitigating the consequences of a release. According to

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Ramabrahmam et al. (1996), two operator roles are the main responsible for plant evacuation: the on-site works main controller (WMC) and the on-site works incident controller (WIC).

The WIC has to direct his team to control the release and operates to ensure the safety of the rest of the plant. In particular, once the WIC receives the call from the incident identifier, he/she has to (CCPS, 1995):

- alert the WMC through telephone/radio;
- concentrate only on containing the source of emissions directing his team to stop loading and unloading operations, and stop all transfer operations in the plant and to relieve the tank pressure through the flare stack;
- activate fire-fighting system/water curtains, etc.
- ensure the safety of the electrical machinery.

Once alerted of a release, the WMC takes charge of the situation and coordinates from the emergency control room all the Emergency Response Team, including different departments, i.e., the Fire, safety and environmental, Personnel, Security and Medical department. He/she has to perform the following main steps (CCPS, 1995):

- inform local emergency authorities, such as fire, police and medical services;
- communicate and arrange additional help for WIC from other plants, if required (under a mutual aid scheme);
- check the wind direction and look for secondary effects;

A schematic representation of the relationships among the main plant evacuation roles is depicted in Figure 3.

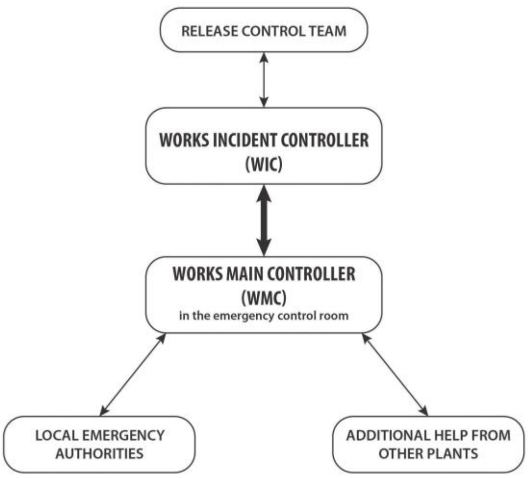

Figure 3. Relationships among main plant evacuation roles.

Due to their critical role, the emergency organization members must be properly trained. For instance, both WMC and WIC should have experience on related risks (what to expect and look for during an emergency), and the capability to respond (and improvise)

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while limiting damage as much as possible. As Ramabrahmam et al. (1996) point out, these figures should be also trained to handle unexpected situations, such as a missing link within the line of command during the accident. For this reason, overall decision competence is another important skill for both the roles. In other words, a good level of resilience skills is expected from WMC and WIC. Having their performance such a strong impact on the accident outcome, a monitoring approach ensuring personnel evacuation success is advisable. This walkthrough application explicitly refers to a game development process focused on the WIC role.

Step 2. The analyst identifies the CSFs and related second level CSFs to be analysed. Table 3 presents Level 1 CSFs, Level 2 CSFs, and an exemplar comparison with traditional GIs and REWIs. In particular, the walkthrough application refers to the CSFs: Response Capacity/ Response (including improvisation), highlighted in grey in Table 1.

Table 1. Main GREWI GEMs and corresponding REWIs for the walkthrough application. Highlighted in grey the walkthrough application referring to Response Capacity/ Response (including improvisation).

Level 1 CSF	Level 2 CSF	General issues	Corresponding REWIs
Risk awareness	Risk understanding	System knowledge	WMC/WIC: no. of years of experience with NH3 production.
		Information about risk	WMC/WIC: no. of hours of risk courses in the last 12 months.
		Information about the quality of barriers (technical safety)	WMC: barrier failures e.g. PRVs failures, or no. of hours of maintenance backlog in the last 6 months.
	Anticipation	Risk/hazard identification	WMC/WIC: has the operator ever participated in a general HAZID?
	Attention	Process disturbances	WMC: no. of alarms not acknowledged within X minutes in the last month.
Response capacity	Response (incl. improvisation)	Training	WMC/WIC: no. of exercises completed by the operator each month.
		Handling of exceptions	WMC/WIC: no. of exceptions handled in the last month
		Ability to make corrections and decisions	WMC/WIC: no. of cases in which a decision to respond has been delayed in the last three months
	Robustness of response	Communication between actors	WMC/WIC: no. of cases in which communication between WMC and WIC has been inadequate in the last 6 months.
	Resourcefulness	Adequate staffing allocation	WIC: no. of cases in which staffing has been inadequately allocated in the last 3 months.
Support	Decision support	Adequate external decision support	WMC: total no. of positions available for decision support at the end of each month.

Step 3 (a). For the Level 2 CSF "Response (including improvisation)", the GREWI analyst - based on Table 2 (Appendix 1) - prioritizes two GMMs: Physics, and Progression. Tactical Maneuvering might be considered as well, but with a lower priority. Internal Economy should thus support the development of the gamified CSF indicators related to at least Physics and Progression, and then, possibly to Tactical Maneuvering.

Step 3 (b). Starting from Physics and Progression, the analyst chooses the most suitable GDPs, based on Table 3 (Appendix 2). In particular, for the purpose of the case study, some GDPs are considered in the next phases: Static Engine, Dynamic Engine, Static Friction, Stopping Mechanism, Escalating Challenge, Multiple Feedback, Worker Placement and Slow Cycle. The next substep clarifies their usage in the game development context.

Step 3 (c). Since the game development mainly focuses on the analysis of the WIC role, it is necessary to develop a game which is appropriate for ensuring he has a good response in case of a critical event. This is a simulation game, in which the player (i.e. the WIC) has to check the initial state of the plant, identify criticalities, and provide a good response strategy to deal with them (i.e. assign all the required tasks to a team of operators assembled after the incident).

Initially, the WIC avatar moves on the map, through simple keyboard commands (arrow keys). The purpose of this game phase is to simulate a site inspection to identify the area of ammonia release (Figure 4a). Note that, in this early phase, the Graphical User Interface (GUI) provides the following feedback (referred to quantifiable aspects, as the GMM "Internal Economy"): 0/5 engaged operators (which inherently suggests the goal of the game: reach 5 engaged operators), 25 available stars and elapsed time. Note that stars represent points that could be associated with a measure of player's energy: the higher the better, and the game lasts until the number of stars is higher than 0.

If the action play time exceeds an allowed upper bound of 3 minutes without finding the location of the ammonia release, the game will be over (Figure 4b). Such result in the early stage of the game might represent an

indicator of poor participation in the game or poor knowledge of the plant, especially when combined with the number of attempts to complete the mission.

When the WIC finds the release location (Figure 4c), he/she concludes the introductory mission, and starts the second stage of the game. It is worth noting that the exact location of the release is generated at runtime in an area of the plant with probability proportional to the actual estimated risk, i.e. higher risk zones will have higher probability for a release. This latter feature ensures that trained and skilled players might take a time advantage in this phase, knowing which are the locations for probable and severe releases. The player should be implicitly motivated to look for the place of the accident as soon as possible, and by doing that, he/she starts acquiring a deeper knowledge of the plant layout. Note that, in the current version of the game, the plant is represented by a two-dimensional map obtained through Google Earth Pro, but more realistic reproduction could be considered such as a three-

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dimensional environment and first-person perspective. The core pattern of the game is a Worker Placement GDP, whose workers are operators that must be engaged in the plant's restoration activities. A Static Engine produces the initially Wandering (uncommitted) operators on the map. Contemporarily, the player develops personal strategies for dealing with the site inspection, i.e. where to start, which is the shortest path to reach different locations, prioritizes inspection routes to locate other operators wandering in the site.

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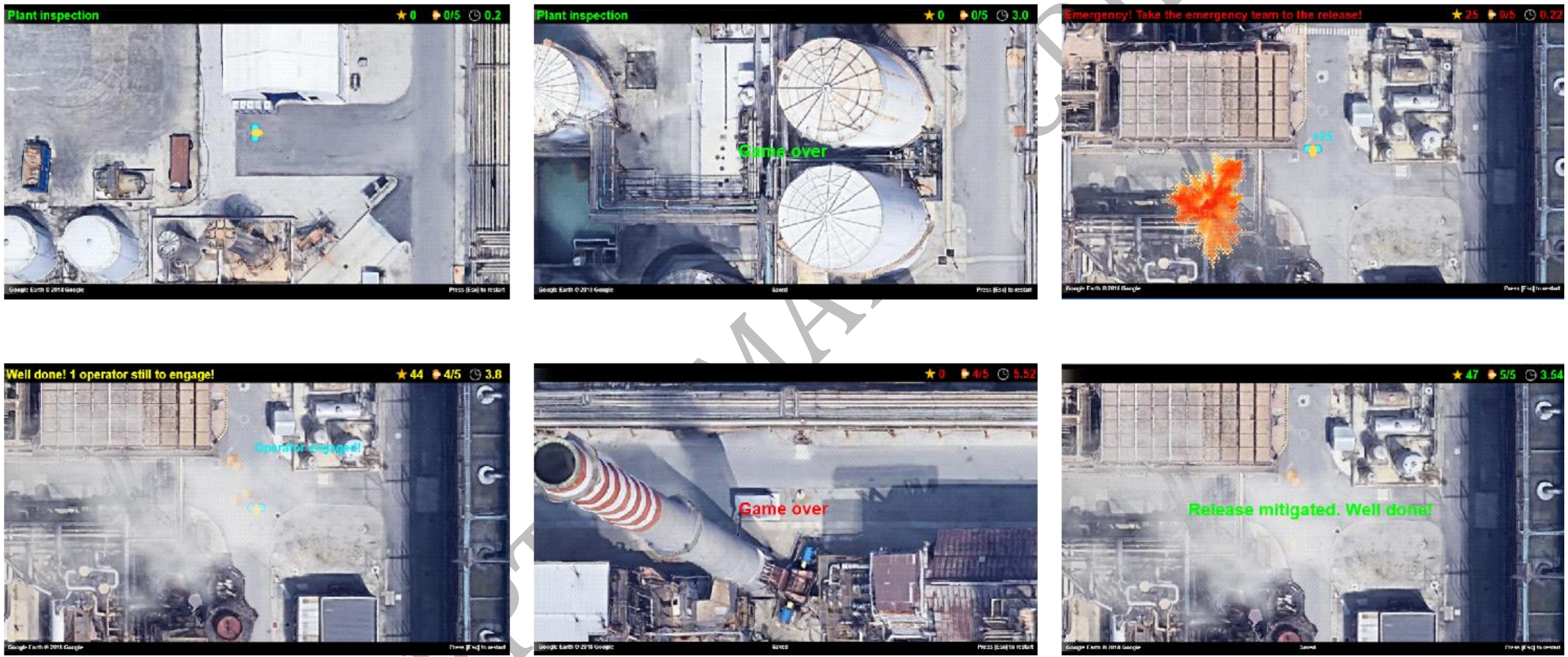

Figure 4 a) First game phase of plant inspection; b) game over due to no detection within 3 minutes from the start; c) detection of explosion followed by release; d) phase of engagement of operators; e) game over due to a release too large to be mitigated, i.e. zero stars; f) 5 operators engaged and game won.

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Once detected the release location, the GUI shows the message: "Emergency! Take the emergency team to the release!" and the stars gauge begins to count down. The WIC has to deal with two different events: a large release and a small release. Following ARAMIS (Andersen et al., 2004), the definition of large and small releases are, respectively, the following:

- 100 mm diameter of breach or full bore rupture for a pipe leak, and
- 10 mm diameter of breach or 10% of the pipe diameter for a pipe leak.

In terms of GDP: Slow Cycle sketches two degrees for the two types of releases.

From now onward, the game target is: engaging a minimum response team (Figure 4d), which the operators should know, by procedure, to be constituted by 5 operators. In this phase, the stars gauge decreases its value over time and represents the ammonia still available in the plant: one star lost every four seconds (every three seconds in the large release case). The game is over when the release becomes too large to be mitigated, i.e. when the number of stars reaches the zero value (Figure 4e). This mechanism represents a generic Static Friction GDP, in turn, part of a larger assembled pattern: Escalating Challenge. On the contrary, the game is won when all the 5 operators are engaged and the release is mitigated (Figure 4f). In this case, the GUI displays the following message: "Release mitigated! Well done!"

While time is running (and stars are decreasing), the WIC avatar has to look for operators on the map. When an operator is found, touching it changes its status from Wandering to Recruited, i.e. the operator starts following the WIC avatar's movements in the plant. The player must lead one or more Recruited operators up to the release location in order to change their status into "Engaged", being careful not to leave them behind. If the WIC avatar is moved too fast or the operator gets stuck in the environment, then their mutual distance increases resulting in a change of the operator's status from Recruited to Lost (GDP: Stopping Mechanism). The WIC-operators distance's behavior is implemented by coupling a Static Friction with a Dynamic Engine, whose functioning depends as much on the operators already Engaged, as on the ones in Recruited state. In this way, with a lowering number of Wandering operators, it is preferable to recover possible lost operator than to recruit new ones. This superstructure puts in practice the Multiple Feedback pattern. The player must reach and touch again the lost operator to make him return to the recruited state. When the status of an operator changes to Engaged (operators working at the release site), the star counter is increased by +15 and the engaged operator counter by +1. The gameplay's double conflicting dynamic (i.e. hurrying to bring the operators to the target location and at the same time minimising the distance from the operators) grows into difficulty as the time passes by and refers to the GDP Escalating Challenge. The simultaneous presence of conflicting objectives, dynamic elements such as erratic operators and variably generated ones (e.g., place of release, severity of the explosion) forces the WIC to adapt in a timely manner to conditions that do not occur in the same way, promoting his/her progression, adaptive capacity, and somehow training his/her resilience potential.

Step 3 (d). About GEMs, the main focus is on Individual Score, Team Score and Duration. For this latter, it is taken in consideration the total play time (since game start to game end), as well as the player's timestamp associated with the release location identification. Consequently, in terms of GEMs usable as a proxy measure of the Level 2 CSF, the GREWI analysts can define:

- Inspection_training = Release detection time / Maximum release detection time
- Response_training = (Total play time - Release detection time) x Number of operators engaged / 5
- WIC_Responsiveness = Total number of stars collected by player(i) / Total number of played games by player(i)
- TEAM_Responsiveness = Total number of stars collected by all players / Total number of played games by all players

The GEM "Inspection_training" is a metric that provides a proxy measure of the player's training level about the plant layout and the associated risks zones: low values of Inspection_training reflect short time required to detect the release, implying that the WIC properly prioritizes the riskier locations. The GEM "Response_training" aims to combine the time required for a response and the effectiveness of the response, i.e. number of operators actually engaged over the number of operators required (5). These two metrics can be calculated for each played game. On the contrary, "WIC_Responsiveness" is intended to be an overall score for a single player, while "TEAM_Responsiveness" is intended to be a team metric for defining the overall performance of the WICs in the entire plant. The choice to provide a metric not explicitly based on the number of games won or lost, but rather on the neutralized value of collected stars, derives from the decision of avoiding bimodal representations: the proposed metrics provide an assessment of multiple levels of adaptive and response capacities, and as a side effect, might increase players' engagement (e.g., for scores in a leaderboard). Figure 5 shows the GREWI canvas for the case study at hand.

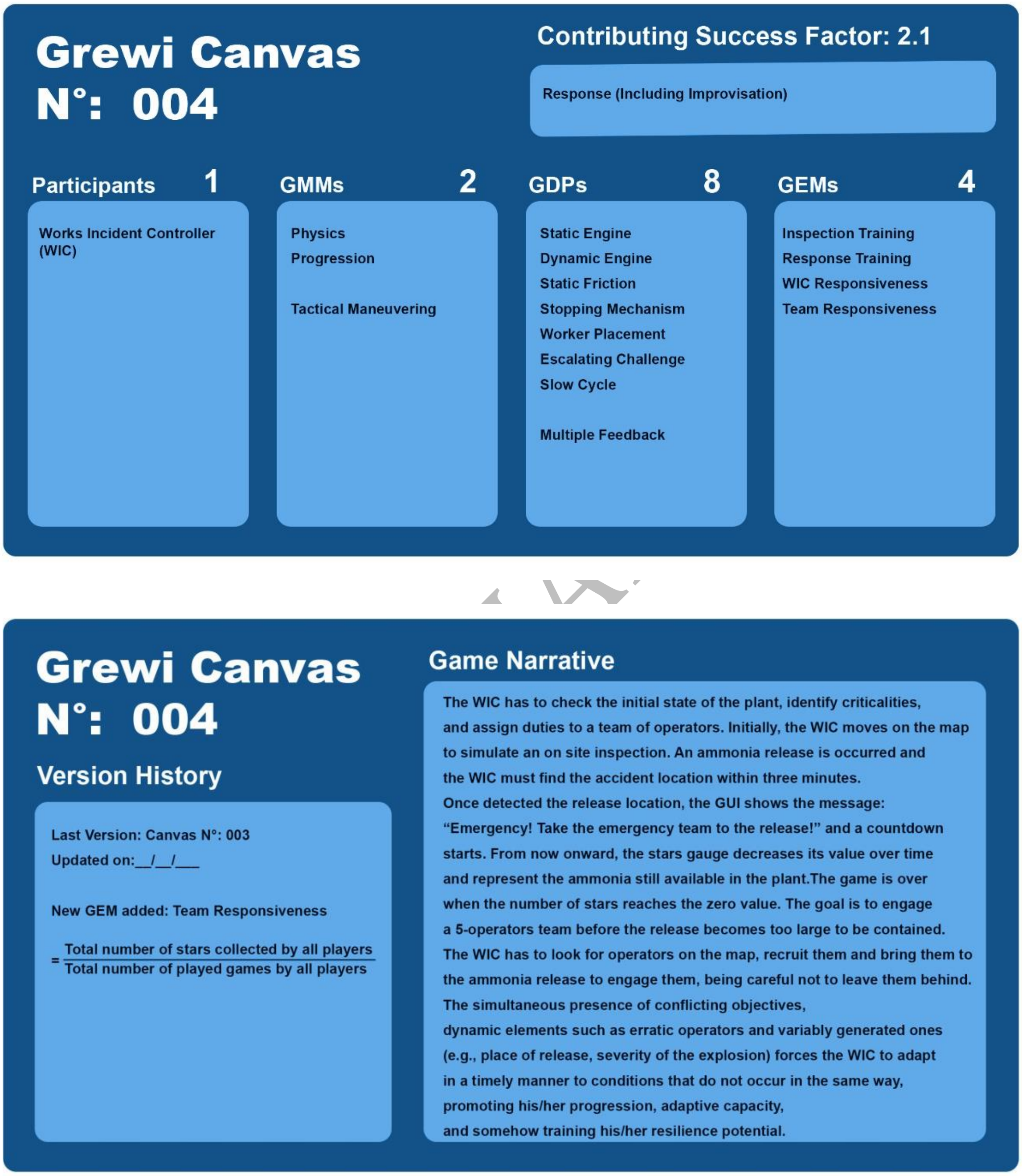

Figure 5. Example of a possible GREWI canvas for the CSF "Response (including Improvisation)"; Front side (above panel) and back side (below panel).

Step 4.

Once the selected GDPs have been encompassed into a game's narrative, the analyst got the necessary elements to the construction of a simulator. A valuable framework has been proposed in literature to test the effectiveness

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of mechanisms and patterns (called "machinations"), and currently used for testing game patterns from the earliest stages of game design (Adams and Dormans, 2012). Such approach has been used in this research to check the consistency and significance of the game, as well as to obtain a probabilistic estimation of the duration and scores. The simulation is implemented with a particular type of directed graph called machinations, which accounts for the flows of different resources – which can be both tangible and intangible – across the solid archs (Resource connections) between different kinds of nodes.

The very basic node of a machination graph (the circle) is called Pool and it is a container for resources. A triangle pointing upward is a resource generator (Source), while a downward triangle is a Drain. A marked triangle pointing to the right is a Converter from one resource to another kind of resource. (e.g. an engine, can be modelled both with a Source and a Pool containing the resource “thrust”, and by a converter with “fuel” as input resource and “thrust” as output resource). Besides the resource connection, the tool allows also for State connections (dashed arch) which modify at runtime the flow rate of the resource connections, trigger different events or activate/inhibit their target nodes. The diamond shape nodes are called Gates and redistribute Resources, without collecting them. A gate with a die selects randomly its outputs. A white box encompassing a black box is an End condition which, determines the end of the game if the condition labelling the state connection is verified. A black box is a special node for building user defined functions. it is possible to implement the logic programming and several kinds of feedback/feedforward loop. Moreover, every node can run in different activation node: running automatically at every step (marked with “*” sign), running once at the beginning of the simulation (“S”) or passive (no special sign). The resource flow is determined by the label on the connection (1 is the default value). An “&” sign indicates that all the resources are allowed to flow at the same time. The circle with the inner hourglass permits to establish a delay in the flow. As an example, the slow cycle pattern highlighted in yellow is made of a random gate activated in the beginning which, with equal chance, activates the static engine of a generic resource. The begot resource within the pool makes the condition "not equal to zero" true, triggering the corresponding branch of the static friction which depletes the stars. Similarly, the Stopping mechanism (highlighted in orange) limits the process of recruiting operators. Appendix 3 contains a description of all GDPs and the table that maps the various GMMs in the GDPs.

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Figure 6 shows the prototype of our game, built with the machinations tool and regarding the thorniest stage of the gameplay. The tool is equipped with atomic elements that, once combined, form the various GDPs (as highlighted with different colours in the figure). Moreover, once the simulation is running, it allows to give a dynamic description of the game and the states in which it may incur. Different GDPs are highlighted with different colours in Figure 6. The pattern at the heart of the game is the worker placement trivially consisting in “engaging” a 5-operators team. As further example, the slow cycle pattern highlighted in yellow is made of a random gate activated in the beginning which, with equal chance, activates the static engine of a generic resource. The begot resource within the pool makes the condition "not equal to zero" true, triggering the corresponding branch of the static friction which depletes the stars.

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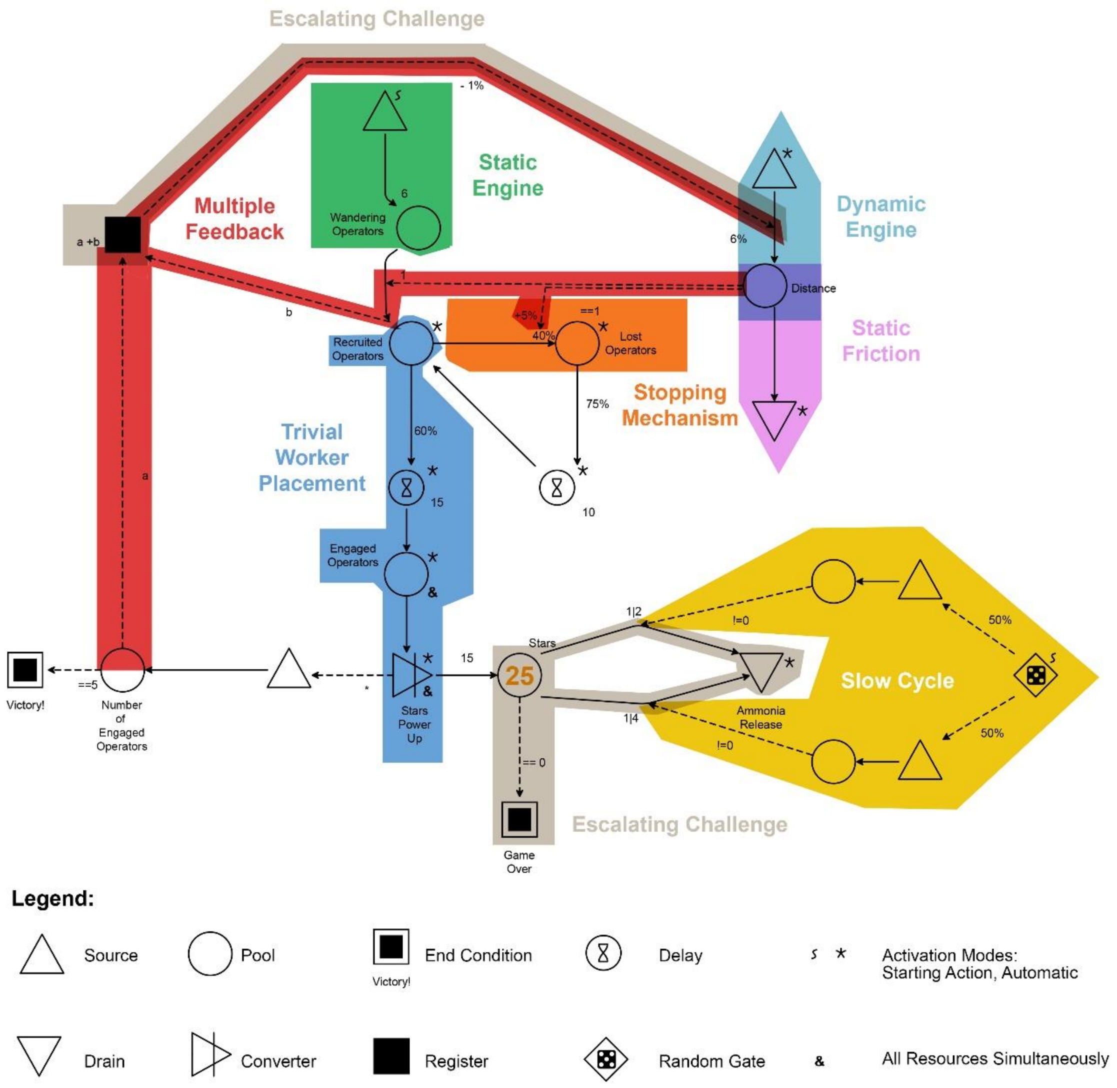

Figure 6 The prototype of the game about the ammonia release simulation described with the Machination framework.

Figure 7 has been built overlaying 200 simulations generated by the simulation prototype model both for the stars resource and for the engaged operators. The simulation ended in Victory (i.e. 5 operators engaged before the time limit) 172 times (86% of the simulations), with an average elapsed time of 132 seconds. The 0, 1, 2, 3, 4 quartiles referring to Victories are respectively 43.5, 96, 123, 168 and 300 seconds.

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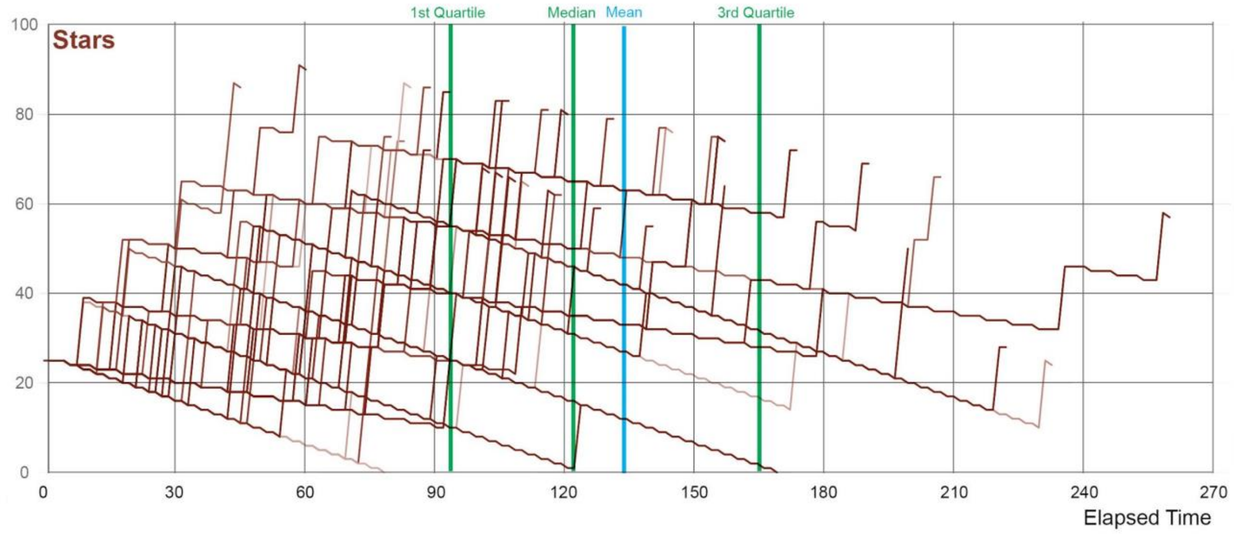

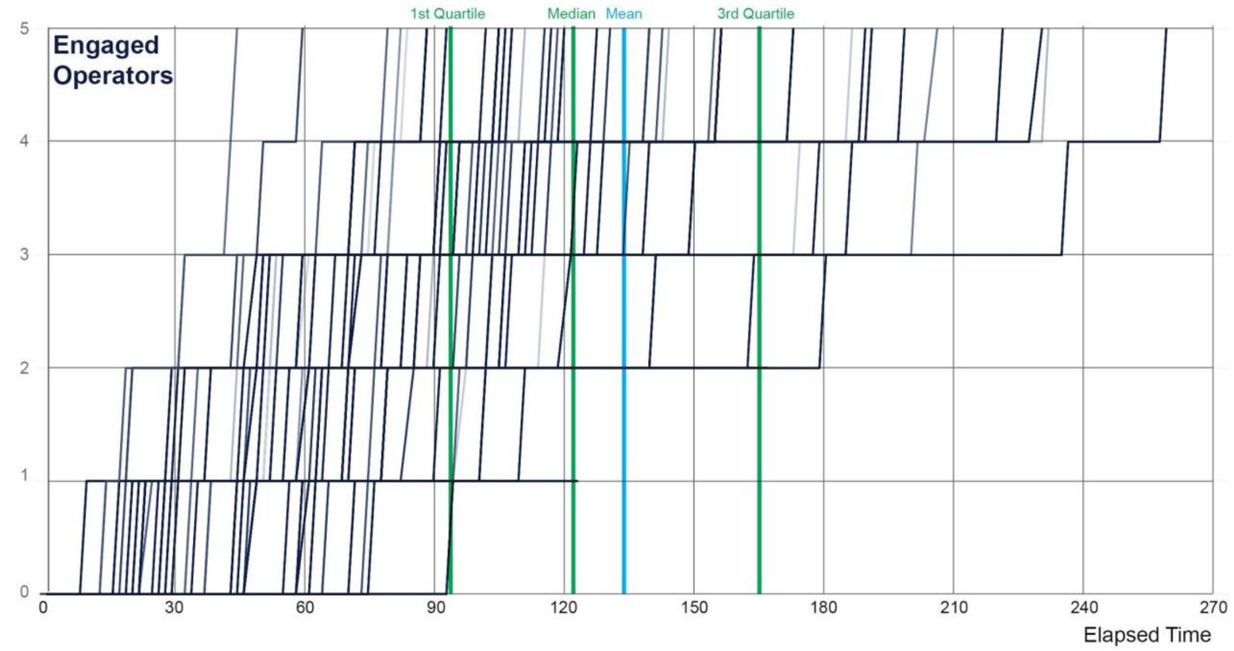

Figure 7. Simulation results of the machination model. The above panel illustrates the stars evolution for the 200 run simulations, the panel below the evolution of engaged operators. Note that the quartiles refer only to the Victories.

The results of the simulation supported the implementation phase, giving an estimation of the duration and of the expected scores. It is worthy noticing that the game has finally developed has been also refined with the results of the simulation (e.g., assigning the star decrease rate for obtaining acceptable victory percentage, or defining the values for the modelling the effects of distance).

Following the simulation, the game has been implemented with the software "Construct 3" (Scirra, 2019) and published at the following link (where it can be freely played on laptops): https://bit.ly/Plant_Emergency. Engineering students enrolled in the course of "Risk Analysis" were asked to play and test the game.

Step 5. Even if the case can be considered as a toy case study, it is possible to obtain a sketch of GEMs. A total of 22 people played the game 59 times for a total time of 153 minutes. In order to show examples of GEMs, two teams were artificially created considering the first 6 players that played the game between 2 and 4 times – first 3 players in team 1 and the remaining 3 players in team 2.

Figure 8a shows that team 1 does not gain any star for the first 3 games, (meaning that the games are lost), but they win game 4 with about 30 stars. On the other hand, team 2 starts with winning the first two games, but they have a decreasing trend in terms of stars (respectively 50 and 20), up to the loss in game 3. However, game 4 represents a new win for team 2 with about 30 stars. Figure 8b shows that the two teams have comparable total play times per game. The average inspection training values (Figure 8c) show more effective inspections carried out by team 2, except for game 4, where team 1 shows a release detection in relatively little time. The average response training values (Figure 8d) reflect better performance in terms of emergency response for team 2 during all the games. Finally, the overall responsiveness (Figure 8e) of team 2 is about twice the responsiveness of team 1, demonstrating team 2 has better capacity to react quickly and positively to the simulated emergency.

Step 6 and 7. These steps are out of the scope of this methodology walkthrough, but GEMs (and eventually GDPs) may need to be regularly updated for real applications. Moreover, such gamified activities may be integrated with consolidated activities, such as audits or trainings.

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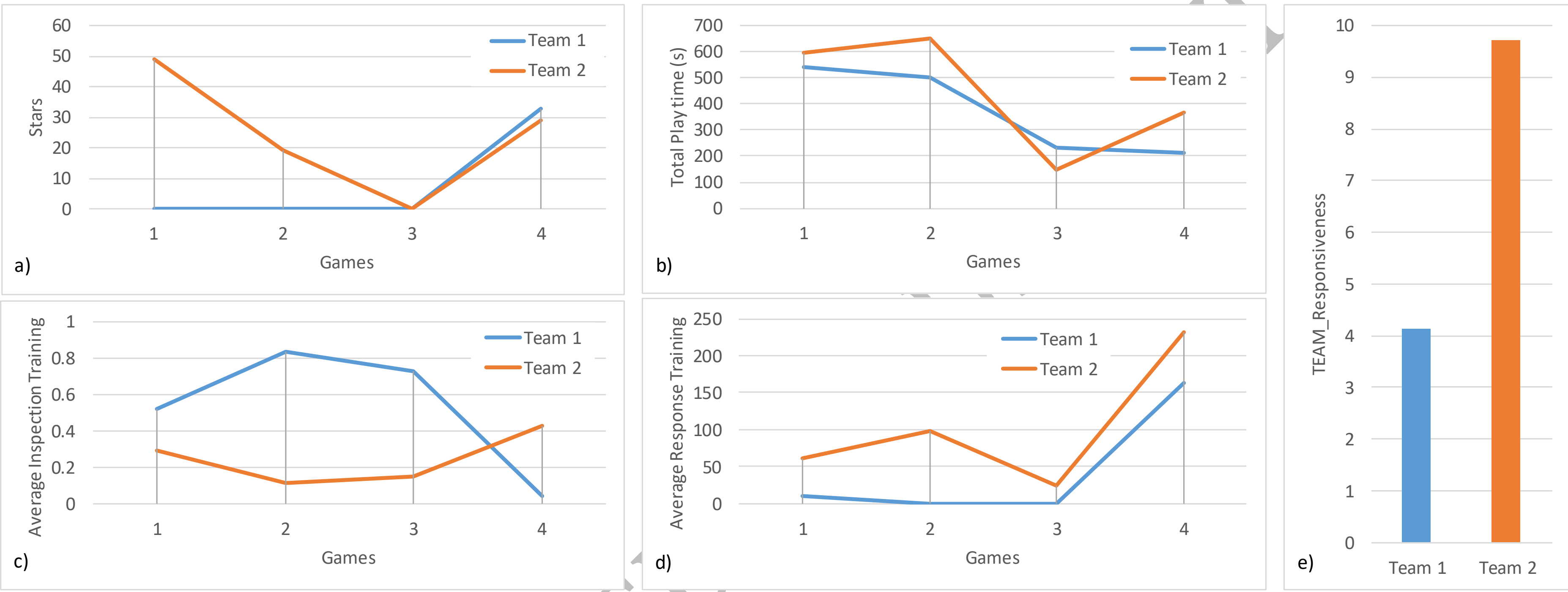

Figure 8. GEMs from case study. a) Team stars per game; b) Team total play times per game; c) Team average inspection training per game; d) Team average response training per game; e) Overall team responsiveness.

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6. Discussion

As explained in §3, the CSFs receive more relevance in GREWI than in REWI. The focus on Level 2 CSFs, rather than on the fourth-level indicators REWIs, represents a choice not to excessively prescribe the data gathering, shifting thus from "what can be measured" towards "what should be measured" (Webb, 2009). Consequently, it is possible through the systematic development and adoption of the GREWI canvas - and ultimately defining the GEMs - to obtain proxy information on system resilience potential. The GREWI, decluttering the REWI, adopts a perspective where safety is not restricted to a reactive approach, analysed *ex post* as a system property. The GREWI abides by the REWI's target to develop indicators that may proactively give information on the system's state, focusing on human variability, as prescribed by the Resilience Engineering theory. Depending on the canvas, the GREWI allows for both personal and process safety indicators through GEMs that may provide proxy measures for them (Baker et al., 2007).

More importantly, the GREWI aims to propose a possible enhancement for the issues of user engagement as means to assess reliable information on system performance. Moving away from traditional thick-box surveys, the GREWI is intended to leverage the human, and social dimension of the organization. It aims to empower the employees' knowledge to support the development of a healthy multilateral safety culture to integrate traditional top-bottom safety audits.

The REWI data collection follows an iterative model where the fourth level indicators can be revised after each iteration and, consequently, the related data gathering methods (e.g., interviews) needs to be re-planned. On the contrary, the GREWI method allows a more flexible information collection process, through run time adaptation of the games defined in the GREWI canvas (Step 6), (e.g.) modifying points or reward at run time, or run-time adding a new safety barrier emerging from the game itself, even in a simulated environment, through GDP machinations. In fact, at some levels of abstraction, both the GREWI canvas and the developed games can be reused and adapted for similar needs (i.e., within the same or different experiences inside an organization).

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7. Conclusion

It is worthy to notice that, with respect to existing works as (Kanat et al., 2013), (De Nicola et al., 2017), (Bontoux et al., 2016), (Bellamy et al., 2018) that present only corporate gamification definitions and experiences, here we describe a full-fledged method to structure serious games for safety-oriented analyses.

The main drawbacks about the GREWI could be the efforts required for game design and the difficulties arising for creating effective and engaging games, properly balancing utilitarianism and hedonism. However, it should be considered that today there are several IT tools to support game design, which in some cases requires limited coding knowledge. Secondly, it should be observed how gamified experience may contribute to create a healthier working environment, empowering operators' direct feedback, stimulating participation and representing the starting point for meaningful discussions, training updates, or even, enhanced individual sense-making.

It could be also expanded the current perspective on serious games, by employing other gamification techniques aimed at both enhancing the engagement of the operators, but also at improving the quality of the information provided. In this regard, it could be developed a framework for relating the information quality dimensions to the resilience indicators, (e.g.) starting from (Pipino et al., 2002).

Future research directions should thus support GREWI analysts through the development of multiple case studies, successful stories, and best practices in operating scenarios, ideally feeding a repository of GREWI canvases. In this regard, if paying more attention to the physical dimension of the game, it could be also strengthen the technical perspective of the analysis (currently limitedly include in both REWI and GREWI), providing (e..g) game environments more aligned with the technical aspects of a system.

Extending the concepts of serious games to gamification in general, there might be even possible to implement electronic gamified data collection activities, which would allow for easier continuous update and assessment of the GREWI indicators. Despite the growing popularity of the organizational resilience as a conceptual perspective for safety management, the complexity arising from its pragmatical and dynamic implementation into business process (as for the GREWI) may still be seen with scepticism in some industrial environments (Hollnagel et al., 2008). Therefore, an electronic gamified environment may be recommended to lay the ground for dynamic data analysis, allowing continuous improvement of the information gathering outcomes and systems' performance. At the same time, an electronic GREWI (to be developed after a thorough cost-benefit analysis), would partially mitigate the need for resources at run time, particularly severe in case of large processes.

Acronyms

CSF: Contributing Success Factor

GDP: Game Design Pattern

GEM: Game Element Metric

GI: General Issue

GMM: Game Macro Mechanic

GREWI: Games for Resilience-based Early Warning Indicator method

GUI: Graphical User Interface

REWI: Resilience-based Early Warning Indicator

SME: Subject Matter Expert

WIC: Works Incident Controller

WMC: Works Main Controller

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Appendix 1 – Level 2 CSFs vs GMMs

In this annex we present the tables used to implement the GREWI method presented in Section 4. Table 2 presents the links between Level 2 CSFs and GMMs. Based on the definition of CSFs in (Øien et al., 2012) and those of GMMs in (Adams and Dormans, 2012) (in the book labelled just "mechanics"), the five authors of this paper individually categorized each Level 2 CSF. The categorization process followed a standard polythetic approach available in literature (Wheaton, 1968): each Level 2 CSF was examined in terms of the presence or absence of a relationship with each GMM: "1" indicates presence, and "0" absence respectively. Afterwards, in a focus group conceived to refine the assessment collectively, it was defined a synthetic index (Score) as the sum of the "1" provided by each author: higher values of the Score implies that authors generally agree on the relationship between the Level 2 CSF and the GMM (4 - 5), and vice versa for lower values (0 - 1). Intermediate values, as emerged in the focus group, refer to items which could be possibly related under certain circumstances, and as such their implications should be considered under the specific operational scenario at hand.

Table 2 summarizes the results, where the applicability thresholds as follows:

- High priority. The GMM should be primarily implemented to represent the Level 2 CSF through dedicated GDPs (Score 4 – 5).
- Medium priority. The GMM should be implemented only after the implementation of the High Priority GMMs. (Score 2 – 3).
- Low priority. The GMM allows priority - and might even be neglected – to represent the Level 2 CSF. (Score 0 – 1).

Note that the GMM "Internal economy" has not been considered explicitly in the relationships between CSFs and GMMs because it is always used for providing quantifiable items in relation to each one of the other GMMs.

Table 2. Level 2 CSFs vs GMMs.

	GMM			
	Physics	*Progression*	*Tactical Maneuvering*	*Social Interaction*

Patriarca R., Falegnami A., De Nicola A., Villani M.L., Paltrinieri N. (2019) Serious games for industrial safety: An approach for developing resilience early warning indicators, Safety Science (0925-753), Vol. 118, pp. 316-331, doi: 10.1016/j.ssci.2019.05.031.
Available at: https://www.sciencedirect.com/science/article/pii/S0925753518312037?via%3Dihub

Level 2 CSF	*Risk understanding*	HIGH	LOW	HIGH	MEDIUM
	Anticipation	HIGH	HIGH	HIGH	LOW
	Attention	HIGH	MEDIUM	HIGH	LOW
	Response (including improvisation)	HIGH	HIGH	MEDIUM	MEDIUM
	Robustness (of response)	HIGH	HIGH	HIGH	HIGH
	Resourcefulness/rapidity	HIGH	HIGH	MEDIUM	HIGH
	Decision support	LOW	MEDIUM	HIGH	MEDIUM
	Redundancy (for support)	LOW	MEDIUM	LOW	HIGH

Patriarca R., Falegnami A., De Nicola A., Villani M.L., Paltrinieri N. (2019) Serious games for industrial safety: An approach for developing resilience early warning indicators, Safety Science (0925-753), Vol. 118, pp. 316-331, doi: 10.1016/j.ssci.2019.05.031.
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Appendix 2 – GMMs vs GDPs

The GDPs support the design of a serious games. Table 3 summarises the existing relations between GMMs and GDPs as expressed in (Adams and Dormans, 2012). The table highlights relationships of the different GDPs with the other GMMs.

Table 3. GMMs vs GDPs

			GMM			
			Physics	*Progression mechanisms*	*Tactical Maneuvering*	*Social Interaction*
Game Design Pattern	*Engine*	*Static*	■	■	■	
	Engine	*Dynamic*	■	■	■	
	Engine	*Converter*	■	■	■	
	Engine Building			■	■	
	Friction	*Static*	■	■	■	
	Friction	*Dynamic*	■	■	■	
	Stopping Mechanism		■	■		
	Attrition				■	■
	Escalating Challenge			■		
	Escalating Complexity		■	■		
	Arms Race				■	■
	Playing Style Reinforcement			■	■	
	Multiple Feedback				■	
	Trade					■
	Worker Placement			■	■	
	Slow Cycle			■	■	

Patriarca R., Falegnami A., De Nicola A., Villani M.L., Paltrinieri N. (2019) Serious games for industrial safety: An approach for developing resilience early warning indicators, Safety Science (0925-753), Vol. 118, pp. 316-331, doi: 10.1016/j.ssci.2019.05.031.
Available at: https://www.sciencedirect.com/science/article/pii/S0925753518312037?via%3Dihub

Appendix 3 – List of GDPs

This section provides a summary of the GDPs used in game design. The complete list, application examples, and specification of the GDPs is included in (Adams and Dormans, 2012).

- *Static Engine*

This pattern produces a steady flow of resources over time for players to consume or to collect while playing the game. The principal related patterns to it are Static Engine, Converter Engine and Slow Cycle.

- *Dynamic Engine*

This pattern produces an adjustable flow of resources over time for players to consume or to collect while playing the game. Players can invest resources to improve the flow. The core of a dynamic engine is a positive constructive feedback loop. The principal related patterns to it are Dynamic Engine, Engine Building, Static Friction and Worker Placement.

- *Converter Energy*

This pattern is made of two converters set up in a loop creating a surplus of energy that can be used elsewhere in the game. It is a kind of engine that offers more design possibilities than a dynamic Engine but also needs a little energy available from the very beginning otherwise the process will not start. The converter engine introduces the chance of deadlock and can be very complicated, requiring more work from the player. It is often well suited in combination with Engine Building and some sort of Friction. The Worker Placement pattern can elaborate the converter Engine.

- *Engine Building*

A significant portion of gameplay is dedicated to building up and tuning an engine to create a steady flow of resources. The Engine building is frequently used to create a game that focuses on building and construction and/or long-term strategy and planning. Related patterns are: Multiple Feedback to increase the difficulty of the engine building pattern; All Friction patterns are suitable to balance the typical positive feedback created by an implementation of engine; the Engine Building pattern can be elaborated by the worker placement pattern through evolving both the dynamic and the Converter Engines.

- *Static Friction*

A drain automatically consumes resources produced by the player. It is opposed to the Static Engine. Other related patterns are: Converter Engine, Engine Building, Dynamic Friction or Slow Cycle.

- *Dynamic Friction*

A drain automatically consumes resources produced by the player and the consumption rate is affected by the state of other elements in the game, e.g. when a scaling mechanism with player's progress is desired. Since Dynamic Friction is a good way to balance any pattern that causes positive feedback, it is often part of the Multiple Feedback. Other commonly related patterns are: Attrition and Stopping Mechanism.

- *Stopping Mechanism*

This pattern represents the operationalization of the law of diminishing returns. For a Stopping Mechanism to work, the action must have an energy cost, produce resources, or both. The stopping mechanism reduces the effectiveness of an action mechanism every time it is activated by increasing the energy costs or reducing the output of resources. Stopping Mechanisms are often found in systems that implement multiple feedback. A stopping mechanism elaborates the Dynamic Friction pattern. A Stopping Mechanism might be elaborated by a Slow Cycle pattern.

- *Attrition*

Attrition is a pattern allowing players to directly steal or destroy resources of other players that they need for other actions in the game. It is one of the patterns which implement interaction between different players. It works well with any sort of engine pattern. Attrition is a destructive interaction among players, Trade is a constructive one. Other related patterns are Dynamic Friction, Arms Race and Worker placement.

- *Escalating Challenge*

Escalating Challenge implements the increasing difficulty of further progression after a first progress toward a goal. The pattern reduce targets, produces progress or does both. The feedback mechanic increases the difficulty of the task as the player gets closer to achieving the goal. It is related to Static and Dynamic friction patterns.

- *Escalating Complexity*

The game produces complexity and a progress mechanism increases the production of complexity over time. In the Escalating Complexity pattern players try to keep the game under control until positive feedback grows too strong (i.e. complexity immediately increases the production of more complexity). Any type of engine can be used to implement the progress mechanism, more frequently this latter can be implemented as an Escalating Challenge.

- *Arms Race*

It is another pattern allowing interaction between players. Investing resources to improve their offensive and defensive against other players, it introduces many strategic options to explore, typically lengthening the game, e.g. indirect erosion of other's capabilities. Arms Race is used often in combination with Dynamic Engine, Attrition and Workers Placement.

- *Playing Style Reinforcement*

Playing Style Reinforcement, also known as Role-playing game (RPG) elements, encourages specialization and gradually the game adapts to the player's preferred playing style by applying slow, positive, constructive feedback on player actions. It can be implemented using experience points or not. When using experience points, there is no direct coupling between growth and action, allowing the player to harvest experience with one strategy to develop the skills to excel in another strategy. When playing style reinforcement depends on the success of actions, it creates a powerful feedback. In that case, a stopping mechanism is often used to increase the price of new upgrades to an ability.

- *Multiple Feedback*

Multiple Feedback is a pattern used to emphasize the player's ability to read the current game state, and to deal with different game profiles. The most common combination for multiple feedback seems to be fast, constructive, positive feedback coupled with slow, negative feedback. This creates a trade-off between short-term gains and long-term disadvantages. Playing Style Reinforcements and Stopping Mechanisms are typical related patterns.

- *Trade*

Trade is a game design pattern generally used to introduced multiplayer dynamics and social mechanics that encourage players to interact with one other via commerce as opposed to combat. Trade favors players with good

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Available at: https://www.sciencedirect.com/science/article/pii/S0925753518312037?via%3Dihub

social and bartering skills, and it is very easy to implement in board games. Attrition can be a destructive alternative to Trade pattern.

- *Worker Placement*

The player controls a limited resource (also known as "workers" in gaming context) that she/he must commit to activate or improve different mechanism in the game. The limitedness of the workers is the key concept, because it requires the player to change the distribution of the workers during the game to operate the game mechanisms most effectively. Worker Placement is a flexible pattern that can be used in combination with almost any other pattern, in particular: Converter Engine, Engine Building, Dynamic Friction, Attrition and Arms Race patterns.

- *Slow Cycle*

A mechanism that cycles through different states at a slower rate than the other game mechanics, creating periodic changes to the game's mechanics and requiring players to adapt and develop more versatile strategies. The Slow Cycle pattern prolongs the average learning curve aggravating the difference in performance between more and less experienced players. Slow Cycle can be implemented in many different ways, e.g. by alternating between two binary states, or shifting between different states randomly chosen. It is often related to Static Engine, Static Friction, Stopping Mechanism and Worker Placement design patterns.