A NEW EXPERIENTIAL MODEL TO INNOVATE THE STEM LEARNING PROCESSES

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Abstract

It is recognised that many European countries are currently facing a crisis amongst their younger generations in respect of scientific learning vocations. The number of students specialising in science, technology, engineering and maths (STEM) disciplines has been in steady decline in recent years and Europe faces nowadays the concrete risk of an acute shortage of suitably qualified scientists, technicians and engineers. There is strong evidence that for many young people their disengagement from STEM subjects starts during secondary education. The drivers of this disengagement are various but research indicates that there are primarily two factors at play: first, there is a commonly held perception that amongst young people that scientific subjects are difficult to learn and master; second, there are misapprehensions regarding the employment pathways available to STEM students with many young people believing that studying these subjects will lead to poorer pay and a less attractive working life.

Evidence suggests that the teaching of STEM subjects requires radical reform. Immersive, experiential learning and the deployment of self-directed learning approaches can be the catalyst for deepening student engagement and improving learning outcomes. However, too much STEM teaching remains teacher-led, didactic and one-dimensional. At best, this makes the learning experience more challenging in relation to student performance; at worst, potential STEM students are put off these subjects for life due to an inability to fully engage in the content of lessons. For those students who do stick with STEM subjects, their ability to develop the skills and competencies they need to operate effectively within highly technical employment environments can be diminished meaning that employers are required to undertake considerable retraining in order to bring graduates up to speed.

These dual problems – of the attractiveness of STEM subjects to learners and the effectiveness of STEM teaching in relation to learning outcomes – require novel solutions. The NEWTON project – funded under the Horizon2020 E.U. programme - is a large scale initiative to develop and integrate innovative technology-enhanced tools for teaching and learning and to create a pan-European learning network platform that supports fast dissemination of learning content to a wide audience in a ubiquitous manner. NEWTON is seeking to deploy a range of novel techniques and methodologies, such as AR/VR, Fab-Lab, Virtual Labs, user profiling, self-directed learning and gamification – that is the use of game mechanics – and game-based learning (the use of so-called 'serious games') for the engagement of the student and for the enhancement of the learning experience, in general. Within the context of a project of this scale – and one that utilises the many and various elements of a modern learning management system – the authors of this paper have developed a specific model, the Newton Enhanced Gamification Model (N-EGM), which provides a coherent approach to the implementation and use of gamification and game-based learning integrating the concepts of socialization and personalization in an unique solution within a digitally-driven STEM teaching context. This paper presents that model and discusses, in detail, the way in which these elements can integrate effectively with other digital learning tools and technologies as a way of cultivating student motivation, increasing engagement and, ultimately, improving learning outcomes.

Keywords: gamification, game-based learning, STEM teaching, pedagogical approaches to learning, technology enhanced learning.

1 INTRODUCTION

Europe is facing a skills crisis in the area of science, technology, engineering and maths subjects. Evidence clearly supports the idea that, in comparison to other countries and regions around the world, European students are typically less attracted to STEM subjects at school and the uptake of these subjects within high and further education is diminishing. The reasons for this are various but there is evidence that these subjects are not taught in a way that is engaging and dynamic enough and, furthermore, that students are put off the idea of following a STEM pathway as they feel that these subjects are too difficult or that the study of these subjects will not lead to positive employment prospects later in life. As we face the shared and very real dangers of climate change, over-population and diminishing resources, our need to educate the scientists, technologists and engineers of the future cannot be overstated. Every society needs individuals who can contribute something meaningful to addressing the myriad problems that we face at an individual, communal and societal level. This is not only central to our humanity but also to our economy – many of the so-called 'jobs of the future' reside within the science and technology fields and those countries who are able to find, develop and nurture their young people into these careers will be the stronger for it as the 21st century progresses. Building a strong STEM skills base is also vital to inward investment and will ensure that the employment challenges that we face in many parts of Europe are addressed as European scientists and technicians build the businesses of the future.

One could consider our collective inability to attract talented young people into STEM subjects as somewhat ironic. Today, students (and those who teach them) have a range of technologies at their fingertips (literally in some cases) that are accessible, affordable and able to transform the teaching and learning experience. Whilst we see technologies utilised across the curriculum landscape, STEM subjects offer us a hugely compelling and powerful context within which their application can really take off. Technologies like virtual reality; augmented reality; 3D visualisation – all of which are fast reshaping the worlds of business and entertainment – can offer students and teachers enormously immersive learning opportunities that, even a few years ago, were beyond our imagination. However, we are only seeing sporadic use of these technologies in our schools and colleges and the understanding of, and embracing of, these technologies amongst school managers and, crucially, educators remains inconsistent. It is clear that our ability to harness these technologies lies at the heart of our struggle to improve educational outcomes in our schools and colleges and, one could argue, offers us a key to unlocking the passion we so need for STEM subjects.

Alongside our continued engagement with new teaching technologies is a growing interest in a number of different pedagogical models that, correctly applied, have the chance to further increase student engagement and generate more compelling and effective learning experiences for learners. Within this context, gamification – and allied to that, game-based learning – has been an emerging area of interest for educators over recent years and is now beginning to become mainstreamed within schools and colleges around the world. The current generation of school-age young people have grown up surrounded by and immersed in technology – from mobile phones and multi-channel TV to games consoles and the internet. Digital gaming is, within this context, a dominant social activity with a majority of young people playing games of some description on one or a number of platforms and across different devices. Combining technology, games and learning therefore has enormous potential for engaging young people in new learning experiences that could, if designed correctly, both educate and enthral.

This is the context within which the Newton Project - funded by the European Commission under Horizon 2020 – has been conceived. Newton is a large-scale pilot project that seeks to address the challenges we face in Europe in respect of STEM teaching and learning through the implementation of a number of pilot studies that will utilise a range of technologies and pedagogies. The primary concern for Newton is to understand how we can adapt and implement existing technologies as a means of creating greater engagement in – and better learning outcomes for - STEM subjects in schools and tertiary institutions across Europe. Within that context, the project is also seeking to investigate the role that gamification and game-based learning might play in improving learner outcomes and supporting greater enrolment in STEM subjects. Now in its second year, the Newton project has developed a model for how gamification and game-based learning can be integrated into a wider learning experience and what aspects of the learning experiences can be influenced by – or enhanced by – being 'gamified'. This paper briefly explores the ideas of gamification and game-based learning as they relate to the Newton project and then focuses specifically on the Newton Enhanced Gamification Model – our approach to gamification that will be adopted within the project and, we hope, within learning management systems and other technology-enhanced learning platforms across Europe and beyond.

2 NEWTON PROJECT CONTEXT AND SOLUTION

In response to the challenges across Europe relating to STEM teaching (and outlined above), a number of national initiatives have been launched. Many of these focus on designing and developing innovative teaching and learning programmes that both attract new learners and that deliver a high quality, engaging and effective learning experience. However, many of these projects lack ambition and do not have the scale in order to generate real and lasting impact. The Newton Project is different in that it aims to build an innovative e-learning platform focusing on:

- Providing diverse forms of teaching and learning for formal, non-formal and informal education
- Supporting different levels of education from secondary and vocational schools to universities and further learning, fostering reservoirs of talents
- Employing novel content types and presentation technologies based on multi-sensorial and multi-modal interaction with learners
- Creating personalisation and adaptation of content to best match user profiles and their learning environment

In addition, Newton has the task of developing new teaching and learning practices based on novel technologies that are specifically aimed at attracting learners and keeping them engaged. As a part of this, gamification and game-based learning are a key differentiator. The Newton Project is now working to integrate ideas of gamification and game-based learning – that we expand on below – as a way of developing and reinforcing basic knowledge in STEM subjects for learners who are studying in secondary schools and at vocational schools. The aim is to improve teaching practices and thereby increase the level of comprehension and skills acquisition amongst STEM students, partly by ensuring that those students continue to be motivated to learn regardless of how challenging the subject matter seems to be. Within this context, Newton will help to change the perception (and the reality) of STEM subjects as being too difficult or challenging to learn and will also aim to increase the level of engagement and enthusiasm for these subjects amongst STEM students. The project is also extending the focus of innovative learning approaches to learners with special educational needs and we are currently exploring the value of gamification for these students.

As we begin to roll out the pilots, the NEWTON project is deploying what we might now consider the dominant 21st century teaching and learning paradigm whereby the student is the centre of the learning process (moving away from the more 'teacher-centric' approach which characterises much of the didactic teaching that we still see in many classrooms across Europe). This student-centric approach is compelling because it enables different students to learn in different ways and at different speeds. This approach also empowers learners to take control of their own learning experience. The idea is that the student becomes a 'performer' able to proactively control the flow of information according to their specific needs and abilities. By basing the Newton approach on the idea of a personalised learning process, opportunities for gamification and for game-based learning are significantly increased (something we explore below). Moreover, technologies such as Augmented Reality, Virtual Reality and Multisensory Media, also developed and implemented within Newton, could offer further opportunities to create game-based experiences, by realizing STEM experiments at same time as enabling all human senses and extrinsic motivations to be stimulated through appropriate gamified mechanics. Within that context, one of the more ambitious challenges we face consists of integrating different experiential components within a unique solution that is perceived by learners as an emotional game and where the teachers are considered the main actors in terms of their involvement in creating and providing not only learning content but also the right elements and rules to stimulate and engage learners. This integration of advanced visual and sensory technologies with ideas of gamification and game-based learning is truly unique and a critical area of development and evaluation for Newton.

3 GAMIFICATION AND LEARNING

Before we define our approach to gamification within the Newton Project, it may be useful for us to set out our terminology and address what we have witnessed as a common confusion within this field. It is important to recognise the difference between 'gamification' and 'game-based learning'. In the literature review on the subject conducted by Ilaria Caponetto, Jeffrey Earp and Michela Ott (2014), the authors describe how, until fairly recently, the term 'gamification' was typically used to denote the adoption of game artifacts (especially digital ones) as educational tools for learning a specific subject. In other words, gamification was used as a synonym for game-based learning rather than to identify an educational strategy informing the overall learning process, which is treated globally as a game or competition. However, within the literature review, this confusion appeared in only a few isolated cases, suggesting that a certain level of taxonomic and epistemological convergence is underway [1]. For our purposes, we would consider game-based learning as the use of (typically) digital games to promote learning. If we talk about 'gamification', we are thinking more specifically about the application of game mechanics – something we describe in greater detail below - to the learning process. We also recognise that we may, in some cases, see a mixture of both game-based learning and gamification applied to a particular educational setting or learning experience.

When we think about gamification – and the game mechanics mentioned above – we are referring to the dynamics and characteristics that are common to both digital and non-digital games. Game mechanics are defined by Dicheva et al., 2014 as including (but not limited to) the following: points, badges, levels, progress bars, leaderboards, virtual currency, and avatars; point systems that manage the acquisition and spending of points that quantify user performance; badges that are given for special achievements; user ranking based on the received points and badges; published/shared leaderboards that reflect user performance in comparison to other users; levels that show the user's expertise and progress and where the player is in the game; progress bars that provide a percentage-based graphical representation of the players' progress; virtual currency used for purchasing in-game (virtual) goods [2]. The Dicheva study also defines the educational gamification design principles that are most commonly deployed within learning contexts. These include:

- GOALS: specific, clear, moderately difficult, immediate goals
- CHALLENGES & QUESTS: clear, concrete, actionable learning tasks with increased complexity
- CUSTOMISATION: personalised experiences; adaptive difficulty; challenges that are perfectly tailored to the players skill level; increasing the difficulty as the player's skill level expands
- PROGRESS: visible progress towards mastery
- FEEDBACK: immediate feedback or shortened feedback cycles; immediate rewards instead of vague long-term benefits
- COMPETITION AND COOPERATION: social engagement loops
- ACCRUAL GRADING
- VISIBLE STATUS: reputation, social credibility and recognition
- ACCESS/UNLOCKING OF CONTENT
- FREEDOM OF CHOICE: multiple routes to success allowing students to choose their own sub-goals within the larger task
- FREEDOM TO FAIL: low risk from submission; multiple attempts
- USE OF STORYTELLING: including the adoption of roles in the form of avatars [2]

This list is by no means exhaustive but it is instructive in considering the ways in which we might apply game mechanics or, as Dicheva et al have it, 'gamification design principles', to the job of teaching STEM subjects within Newton and beyond. The Dicheva paper goes on to review a range of evidence in relation to the effectiveness or otherwise of utilising gamification design principles within an educational context. The study draws some critical conclusions, namely that the majority of the papers reviewed report encouraging results from the application of gamification, including the finding that gamification can result in the following:

- A significantly higher engagement of students in forums, projects, and other learning activities (e.g., Anderson, Huttenlocher, Kleinberg, & Leskovec, 2014; Caton & Greenhill, 2013; Akpolat & Slany, 2014);
- An increase in attendance, participation, and material downloads (Barata, Gama, Jorge, & Gonçalves, 2013);
- A positive effect on the quantity of students' contributions/ answers without a corresponding reduction in their quality (Denny, 2013);
- An increase in the percentage of passing students and participation in voluntary activities and challenging assignments (Iosup & Epema, 2014);
- A minimizing of the gap between the lowest and the top graders (Barata, Gama, Jorge, & Gonçalves, 2013).
- Hakulinen & Auvinen (2014) conclude that achievement badges can be used to affect the behavior of students even when the badges have no impact on the grading.
- The papers of this group also report that students considered the gamified instances to be more motivating, interesting, and easier to learn as compared to other courses (Mak, 2013; Barata, Gama, Jorge, & Gonçalves, 2013; de Byl & Hooper, 2013; Mitchell, Danino, & May, 2013; Leong & Yanjie, 2011).

When we consider the range of options available in respect of gamification tools and techniques – and then when we gain a deeper understanding of the potential benefits of gamification to the learning process - we can start to see how this could be usefully applied to the challenges outlined earlier in respect of STEM teaching.

Alongside the concept of gamification, we need to also think about game-based learning – that is the use of gaming technology to achieve specific learning objectives. The common appeal of the modern video game experience has not gone unnoticed within wider fields of research and development with many applications being developed for sectors beyond entertainment. The growth of "serious gaming" – that is games that have a 'serious' purpose or objective – has been seen across a range of settings that include education, health and the environment. Within education, it is not hard to see why young learners, given the choice between actively participating in a video game (playing) or passively listening to a teacher (studying), would usually opt for the first and not the second. Games, at their best, are immersive, exciting, engaging – you want to play and play again. In achieving specific learning objectives, the ability to engage learners is vital. The experience of playing – the physical interaction, the competition, the reward, the visible progress and achievement – the player is immersed and fully engaged. Gaming also can involve a collaborative or team aspect which adds further to the immersion of the player. Applied to education, games offer a compelling means of stimulating learner engagement.

The nature of gaming also connects rather neatly to emerging thinking around classroom pedagogy. Video games allow the player to be the hero of their own story and to operate at a level that is comfortable for them. This type of 'user-led' experience is gaining real traction within classroom pedagogy (and, as we mentioned earlier, is the basis upon which we are developing the Newton approach). Anna Craft highlights the how technology can have a profound impact on learning in her book "Creativity and Education Futures: Learning in a digital age". She talks about a learner-centric approach to education and sees this as being partly the result of an increase in the use of technology. [3]. If we are able to capture this idea and turn it into and educational experience, we can see how game-based learning might give us a new and compelling option for learning. Games can also offer us options in terms of user personalisation. Many video games now adapt to the abilities and achievements of the player as they progress. Gaming technology also produces a range of data that can be used inform this personalisation. The progress of each player can be tracked with reports produced on how well the player is doing. This data capture function may offer us a new approach to learner assessment.

Although we believe that the case for implementing gamification and game-based learning within education is compelling – and our early research within the Newton Project bears this out - we also recognise that there are challenges and limitations. First, we must ensure that we do not assume that every student is a committed gamer – game-based learning approaches will work better with some learners rather than others and understanding what type of gamer/learner we are dealing with is essential. Second, educators must be open to the possibilities of gaming and comfortable with the technology being used. There is anecdotal evidence to suggest that the implementation of gaming approaches within the classroom can meet with resistance from educators rather than from students. There is also a third area of concern regarding the efficacy of game-based learning in relation to the achievement of specific learning outcomes. Some evidence-based studies have demonstrated that the learning achieved through games and game-based education can be limited if the game itself is not correctly designed or part of a wider learning approach. Students can become immersed in the game but not retain the learning. Our analysis of the impact of gamification must address this directly. Within this context, the Newton consortium has developed an approach that we believe leverages the best of what gamification and game-based learning has to offer whilst taking account of the challenges that these approaches inherently create. In Section 4 below, we present our model and describe the different elements that will be tested across our large-scale pilots over the coming months.

4 NEWTON-ENHANCED GAMIFICATION MODEL

The Newton-Enhanced Gamification Model (N-EGM) aims to combines different concepts in order to define a new approach to learning within the wider context of promoting student engagement. In fact, the model is defined through a multi-layered interconnected infrastructure with three horizontal and one vertical aspect, i.e. transversal to the first elements as shown in Figure 1:

- Gamification (L1)

- Game-based learning (L2)
- Profiling and Recommendation (L3)
- Socialization (L4)

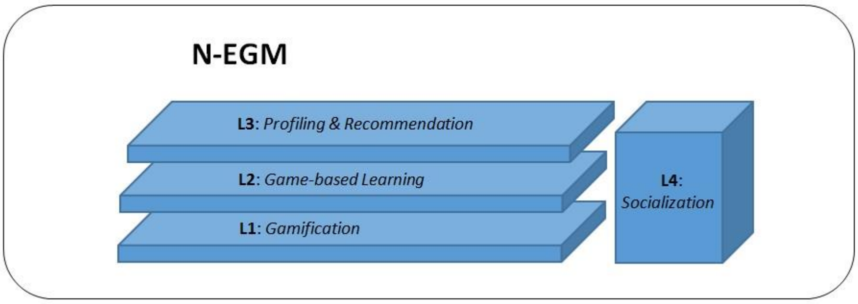

Figure 1: Multi-layer infrastructure of N-EGM.

The application of this model in the domain of STEM education allows to us improve the learning process by stimulating the extrinsic (through gamification mechanisms) and intrinsic (through game interactions) motivations of students. Moreover, since not all students have the same preferences for games, by using/implementing concepts of personalization and adaption (referred to in Layer 3), it is possible to create a system that can recommend specific games based on student profile. Alongside this, socialization layer supports interaction through compliance with current social web tools and, as a consequence, minimises the distance and communication between students and teachers.

4.1 Gamification layer

This layer is inspired by two different frameworks from literature: MDA (*Mechanics*, *Dynamics* and *Aesthetics*) [1] and D6 (*Design Six*) [5], and allows the configuration of gamified mechanics in order to enable a rewarding mechanism to stimulate the motivation and progress of students in their own learning process. In particular, the mechanics consist of:

- Components which are typical elements of a gamification context such as points, badges, levels, certificates, general awards, leader boards, and so on
- Rules representing the combination of actions and conditions which allow players to obtain rewards.

Then, rewarding mechanisms can be seen as a feedback system, in which students or players make some gamified actions and the system reacts by assigning them one of defined rewards.

We remark that in many application contexts, including within a learning context, it is fundamental to create an unique interaction environment (the classroom for example) where each student can compete with colleagues within the same challenging conditions and this can improve the level of engagement.

4.2 Game-based learning layer

This layer is based on the definition of a set of serious games [6] applied in the educational context in order to enable a learning process that is most both appropriate to the learner and immersive through the use of simple concepts such as:

- Dynamics reflecting the run-time behaviour of mechanics subject to input actions and expected outputs
- Aesthetics which are the general user interaction elements stimulating emotions, sensations, wellness, etc.

Our idea consists of describing the dynamics within student experience by defining goals, learning pathways and two types of user interaction (UI):

- Static elements such as textual user interface: we can think about the composition/combination of some mini-games such as check-ins, quizzes, treasure hunts, etc., where students only use text elements to play within system
- Graphic interactive and animated elements, where elements such as avatars, movements, explorations, journey pathways, fight challenges (individual or team) are developed and implemented in the style of a more traditional "videogame"

Although the second approach is generally proven to have better results in terms of the full engagement of players, this requires a greater effort and higher cost in terms of the design and development of a serious *video*-game based on educational content, especially for some of the more advanced STEM subjects (e.g. higher level mathematics).

Finally, each serious game (for both the approaches outlined above) can adopt the Gamification layer in order to define a unique rewarding mechanism and to enable a fully immersive experience through the combination of intrinsic and extrinsic motivations.

4.3 Profiling and Recommendation layer

The user profile is a critical aspect of the model and contains personal and more general user information strictly connected to the behaviour of each player/learner, storing this information as preferences, interests, learning progress, etc. This is a very powerful tool to recommend personalized and adapted game contents and to generate an experience that matches specific players' requirements. In an educational context, this layer is responsible for collecting students' data and provides the tracking and computing of their individual actions in order to update and refine their profiles, so that system can match (and aggregate) different personal learning needs and can recommend the best gamified learning pathway.

The bi-directional connection between Layer 3 and Layer 2 (Figure 2) represents a self-powered production cycle, in which the game behaviour of players feeds their profiles successively to inform their personalized experience.

Figure 2: bi-directional connection between Layer 3 and Layer 2.

4.4 Socialization layer

Since the socialization concept has a steadily greater impact on the technology that we use in our daily lives (and this is particularly true of young people), we believe that social elements can be very useful within the learning context as they allow students to:

- suggest or propose new learning experiences or new ideas for the teaching approach
- help peers during the phase of understanding and learning
- form teams and groups to share their skills and competencies in order to solve problems or simply make progress on some particular learning task, acquiring rewards and benefits as they go
- have a direct communication channel with teachers (or other actors as tutors)
- perform basic social actions (for example "comments" or "share" or "recommend" - aligned to the functions within common social networks like Facebook or Instagram)

Furthermore, the participating teachers can:

- create their own social environments restricted only to other teachers in order to cooperate and discuss the progress of particular students and to explore and build new approaches and solve learning challenges etc.
- join specific students' social groups in order to interact with them and offering further support as a tutor/mentor.

Within the model, this layer is transversal to the other layers in order that students can have a social role in any serious game played, acquire rewards by implementing specific gamification rules to the social actions they take and intrinsically enrich their own profile through their social actions and behaviour, etc.; moreover the Profiling and Recommendation layer could recommend some interesting discussion topic to students.

4.5 What are the typologies of actors?

It is important to define the specific target actors that will be addressed by the N-EGM. These are identified as follows:

- Individual students, teams/groups and students with special needs, such as physical disabilities, learning difficulties, behavioural issues, etc. Then, within their own learning experience each student can be matched with one or a combination of the typologies of players generally characterizing Gamification theory [7], i.e.:
    - Achiever interested in getting rewards and awards
    - Explorer motivated to discover new content, to have new experiences, etc.
    - Socializer stimulated by social interaction, e.g. cooperation, sharing, etc.
    - Killer that wants to be the winner or a leader within their own application context
    - Beginner (someone who is new to games and/or not covered by the previous typologies).
- Teachers or tutors for the configuration of mechanics and some games; in particular they can
    - configure rewarding elements and rules
    - define some mini-games, such as quizzes, using specific configuration tools
    - monitor the students' progress and evaluate their learning experience
    - directly reward students with benefits
    - be an active member of game teams in order to have a direct contact with students

4.6 How to define game-based learning in N-EGM

Our model proposes an approach to defining a serious game within the STEM educational ecosystem based on the archetype of a multi-dimensional journey, where each dimension represents a gamified learning pathway related to one of the STEM subjects and is characterized by a set of mini-games (i.e. nodes) sequentially connected (with a kind of relationship between them), as shown in Figure 3.

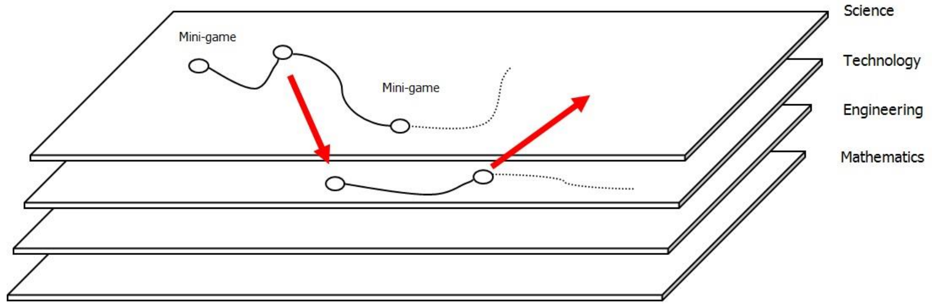

Figure 3: Multi-dimensional learning gamified experience.

An example of our idea can be seen in the following concept: if a student begins a sub-journey in Science, starting from a specific mini-game, he can follow that path and in some cases, he can switch to another sub-journey belonging to the Engineering pathway, in order to create a multi-dimensional journey.

Then, these journeys assume the meaning of “meta-games”, so that they can be developed following a meta-game concept such as “Olympic Games”, “Conquest of the Planets”, “Champions League”, etc., and including typical gamification elements such as points, leader boards, and so on.

5 CONCLUSION

This paper aims to represent a first tentative of definition of a gamification model where multiple concepts are involved and applied in order to address a large number of application contexts. In particular, the Newton Project has provided us, the authors, with the inspiration to develop the proposed solution through the study and analysis of a very critical educational context and involving a number of diverse issues and variables to be considered.

Finally, N-EGM proposes to be not only a guideline for the application of gamification within the Newton Project, but also a reference for

- other R&D&I projects and initiatives
- potential industrial solutions applied in multiple domains (with the possibility of market launch once engineered/adapted)

The next step for the N-EGM – and for the Newton Project as a whole – is to complete the pilots and evaluate the effectiveness of the model within the chosen application fields. We look forward to reporting back on this in due course and our progress will be reported on the project website – www.newtonproject.eu.

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