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DigiFungi: An education software for button mushrooms

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ABSTRACT

The DigiFungi serious game focuses on edutainment for button mushroom cultivation but with the extensibility to be adapted for digital twin applications. DigiFungi is designed to simulate intermediate processes and core activities related to growing button mushrooms species, namely spawn making, substrate preparation, inoculation of substrate with spawn and growth. The gamification of these stages represents an abstraction of a typically complex cultivation process, yet offers the potential to educate user about each of these stages. Gameplay generates a performance score that can be used for measured learning and demonstrative improvement under repetition.

1. Metadata

N	Code metadata description	Please fill in this column
C1	Current code version	*v1.1*
C2	Permanent link to code/repository used for this code version	https://github.com/SCT-lab/DigiFungi
C4	Legal code license	*GNU General Public License (GPL)*
C5	Code versioning system used	*git*
C6	Software code languages, tools and services used	*Blueprint*
C7	Compilation requirements, operating environments and dependencies	*Unreal 5.3.2*
C8	If available, link to developer documentation/manual	https://github.com/SCT-lab/DigiFungi/blob/main/DeveloperNotes.pdf
C9	Support email for questions	will.hurst@wur.nl

2. Motivation and significance

A significant challenge for our future is the sustainable production of food for a growing population but with a reduced environmental impact [1]. To work towards a future where even non-protein food is sustainably produced [2], one possible solution is a greater use of mushrooms [3]. Further, mushrooms, or their mycelia, also offer sustainability solutions beyond mushroom consumption as a crop [4], including sustainable textile alternatives [5], packaging materials [6], bio-composites [7], upcycling of organic side streams, and bio-remediation, presenting a potential impact beyond just food consumption [8].

For button mushroom production in Europe, the cultivation process can typically be divided into distinct stages including 1) spawn making, performed at specialised companies 2a) substrate preparation, involving correct mixtures, temperature control, hygenisation, water and airing; *2b)* inoculation of substrate with spawn and substrate colonization, 3) growth at the mushroom farm, requiring maintenance of airflow, disease observation and moisture level control and harvesting, knowing when to pick. Each stage has unique challenges, data dependencies and ICT resource requirements [9]; this diversity is further exacerbated when considering the requirements for the varied mushroom types. As such, wisdom of the spawn producers, substrate makers and growers plays a prominent role in the quality and quantity of the production of all types of mushrooms, and this is a challenge when training new employees.

The mushroom industry differs between Europe, China, America and India [10] [11,12], thus, the DigiFungi software documented in this article, presents a training tool, extendable to a digital twin software for button mushroom growers focusing on Europe as a starting point but with the potential to be adapted other regions. There are relatively few existing educational fungal tools openly available, however two prominent examples focus on communicating infections and fungal resistance to antibiotics [13] and combinations needed for creating fungus that can survive immune cell attack [14].

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The remainder of this article is as follows. Section 2 provides a description of the software and provides pseudocode for the main game play stages of DigiFungi. Illustrative examples are provided in Section 3, offering and overview of the game play and functionalities. Section 4 outlines the impact of the solution and outlines four potential application scenarios. The article is concluded in Section 5.

3. Software description

DigiFungi, is a modular software developed for button mushrooms, set up as an executable (.exe) file for Windows. The solution is provided on GitHub, available in an open-access format, maintained by the Social Creative Technologies lab at Wageningen University and Research. The tool allows users to go through the aforementioned stages of mushroom production for training process, yet also further extend the application via means of an API to integrate real-world sensor data to cater for digital twin applications. In this section, both architecture and functionalities of DigiFungi are presented.

3.1. Software architecture

DigiFungi was developed in Unreal 5.3.2 on a FireBreather Rapid A59612 AMD Ryzen 9 5900 × 12-Core (24 threads) 3.7GhZ (Turbo: 4.8Ghz) NVIDIA RTZ 3060 12GB, 32GB RAM DDR4 Gskill Ripjaw up to 3600Mhz, Dragon Firebreather catch IT 240 RGB 2 × 120 mm fan with water cooling. The software was developed using the Blueprints system in Unreal which is visual programming language that employs a node-based interface, based on C++, that caters for defining object-oriented classes or objects directly in the Unreal engine. For clarity on the architecture of the Blueprint-specific markup, pseudocode is outlined in the following sub sections.

3.1.1. Substrate process

The substrate process involves a combination of four ingredients (labelled as manure, straw, gypsum and mycelium (which is only added after the heating and cooling), and a cooling procedure to control the substrate heating, specifically for button mushrooms. The gamification of these ingredients in DigiFungi represents an abstraction of what is a typically complex process involving a balance to measuring of each of the substrate ingredients, control of the substrate temperature to prevent overheating [15] but to also eliminate undesirable microbes, pre-watering and measures to ensure that contamination is reduced [15] in order to minimise potential risk to the consumer. Algorithm 1 outlines the pseudocode process for the substrate preparation stage in DigiFungi. During gameplay, a user score is generated and stored to provide an overall performance score. Hardcoded values in the algorithms are based on abstraction of the processes, where specific values are required for button mushroom growth (e.g., 60–80 % water in the substrate).

Substrate Process

```
Algorithm Substrate Preparation
    Input: SubstrateIngredients(A, …n)
    Output: SubstrateCompot
    Enable SubstrateCompot pickup
    for each SubstrateCompot in tray do
        Add SubstrateCompot to MixerTray
    end for
    Add MixerTray to Cooler
    if MixerTray is in Cooler then
        Start HeatProcess
        for i in HeatProcess do
            if i == 14 then
                stop HeatProcess
            else
                Temp increase, Range(10:15)
                i++
                Delay RandomRange(2–5) seconds
            if Temp ≥ RandomRange(60:80) and ButtonPress() then
```

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Substrate Process

```
                Temp - (5–9)
                if Temp > 20 then
                    ChangeTempSliderDisplay
                end if
                if Temp > 90 then
                    Stop HeatProcess
                end if
            else
                !ButtonPress()
                end if
            end if
        end for
    end if
        Add MyceliumComponent
        Return MixerTrayComplete
        Return substrate scores as UnderheatedState, OverheatedState,
    SubstratePerformanceScore
    end Algorithm
```

3.1.2. Growth process

For button mushroom growth, watering typically takes place prior to outgrowth of mushrooms to avoid bacterial growth on the developing mushrooms. The actual growth and watering process within DigiFungi is also an abstraction of a more complex process, where parameters such as moisture content are carefully controlled [15]. In this part of the game, users with completed substrate trays are tasked with controlling the watering and activating the air flow to start venting the substrate, with actions generating a score that is subsequently used along-side the substrate score to provide and overall performance metric.

Growth System Processes

```
Algorithm Vegetative Watering
    Get MixerTrayComplete
    Add MixerTrayComplete to WateringSystem
    For each MixerTrayComplete in WateringSystem do
        Start VentingTimer and Add VentingOption then Delay 4 s
    for i in Watering do
        if i ≤ 8 then
            Add 1 to Watering
        if Watering counter = 8 then
            Disable Watering
        end if
    else if Timer = 35 then
        Disable Watering
        else if Venting enabled then
            Disable Watering
        else if Watering disabled then
            return WateringScore:
            if Range(20:59) then
                return UnderWateredState
            else if Range(60:80) then
                return IdealWateredState
            else
                return OverWateredState
            end if
        end if
    end for
end for
end Algorithm
Algorithm VentingSystemCalculation
    Start VentingTimer
    if VentingTimer < 28 and VentingDisabled then
        add 1.75 to VentingScore
    else if timer < 28 and VentingEnabled then
        save information "vented too soon"
    else if 28 ≤ timer < 56 and VentingEnabled then
        add 1.75 to VentingScore
    else if 28 ≤ timer < 56 and VentingDisabled then
        return OpenedTooLateState
    end if
end Algorithm
Algorithm Mushroom Growth
```

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Growth System Processes

```
        First growth (pinning)
          if VentingTimer = 28 then
            set world scale from 0 × 0 × 0 to 1 × 1 × 1
            return 3DMushroomPin
          else if check disable watering system then
          if disable watering system = true then
            start MushroomGrowthAnimation
          end if
        end if
        CurrentScore = (SubstrateScore + WateringScore) / 2
          if CurrentScore < 35 then
            set morph target (01) value 0.3 × 0.3 × 0.3
          else if CurrentScore < 65 then
            set morph target (01) value 0.6 × 0.6 × 0.6
          else if CurrentScore ≥ 65 then
            set morph target (01) value 1 × 1 × 1
          end if
          if VentingTimer = 56 then
            Start MushroomGrowth
            return 3DMushroomMedium
          end if
          FinalScore = (SubstrateScore + WateringScore + VentingScore) / 3
          if FinalScore < 35 then
            set morph target (02) value 0.15 × 0.15 × 0.15
          else if FinalScore < 65 then
            set morph target (02) value 0.25 × 0.25 × 0.25
          else if FinalScore ≥ 65 then
            set morph target (02) value 0.5 × 0.5 × 0.5
            return 3DMushroomLarge
          end if
      end Algorithm
```

3.1.3. Mushroom score

The final performance score provides opportunity to measure learning progression. As users become more familiar with the substrate and growth parameters during game play, their overall score should increase. The pseudocode (Final Performance Score Process) displays the calculation process, with Fig. 3(A) displaying presentation of the scores of the individual stages to the user. The score calculation is based on the users' performance in each of the substrate and venting challenges within the game.

Final Performance Score Process

```
  Mushroom Score Calculation Process
        Input: ScoreVariableSubstrate()
        for each variable (UnderheatedState, OverheatedState, SubstratePerformanceScore)
      do
          Calculate(VarSubstrate)
          Add(UnderheatedState, OverheatedState, SubstratePerformanceScore)
        end for
        Output: Return(VarSubstrateScore)
        Input: ScoreVariableWatering()
        for each variable (UnderWateredState, IdealWateredState, OverWateredState,
      WaterPerformanceScore) do
            Calculate(VarWatering)
              Add(UnderWateredState, IdealWateredState, OverWateredState,
      WaterPerformanceScore)
        end for
        Output: Return(VarWateringScore)
        Input: ScoreVariableVenting()
          for each variable (OpenedTooLateState, OpenedTooEarlyState, VentingScore) do
            Calculate(VarVenting)
              Add(OpenedTooLateState, OpenedTooEarlyState, VentingScore)
        end for
        Output: Return(VarVentingScore)
        Input: FinalGrowthScore
          Calculate((VarSubstrateScore + VarWateringScore + VarVentingScore) / 3)
        Output: Return(FinalGrowthScore)
        Get(FinalGrowthScore)
          Return (MushroomSize as FinalPerformanceScore)
      end Algorithm
```

3.2. Software functionalities

The game is comprised of a playable environment, involving the aforementioned stages of the cultivation process, as outlined in Fig. 1. For the core gameplay mechanics, the game is comprised of a playable first-person controller (FPC) environment, with a three stage process set up including substrate construction, mushroom growth and a scoring system. Minimum specifications required are i7,32GB RAM, with NVIDIA Quadro T1000 graphics card. Additional functionalities are also included, including a three-tier environment with a mushroom museum containing facts for differing mushroom examples, as later outlined in Section 4.

4. Illustrative examples

The application functionalities were designed under consultation with mushroom experts from seven different countries by means of a structured interview format and leading industrial organisations involved in substrate production, mushroom cultivation and harvest. Recorded information in the interview process related to the main obstacles within the domain, and logging of the main stages of production and considerations for white button mushroom growth. After compiling the findings, the main challenge of the work concerned the abstraction of this domain knowledge into a playable, educational format; resulting in the pseudocode outlined in Section 2. DigiFungi game play examples are displayed in Fig. 2, where A represents the substrate mixture, B is the cooling unit, C the watering process and D the early stage mushroom growth.

Within the game environment, a mushroom avatar is present on screen offering guidelines. In the current version, the text prompts are played on a timed loop and the information was devised in consultation with recognised mushroom experts at Wageningen University and Research. Table 1 lists the five guidelines included.

On completion of the mushroom growth, users are able to pick a mushroom and place it in an analysis chamber. Fig. 3A displays the score screen the users are provided with, with the individual scores of each of the stages visible. Fig. 3B depicts the mushroom museum containing a visualisation of six different mushroom types with facts.

5. Impact

DigiFungi has the potential to impact the practical skills development and knowledge development in and educational and industrial setting. For example, by providing abstracted knowledge of a complex process, the game can lay the foundation for understanding the basic elements of the different stages of cultivation. The game can also serve as a training tool for new employees in the button mushroom industry, supporting them with the quick uptake of necessary skills and

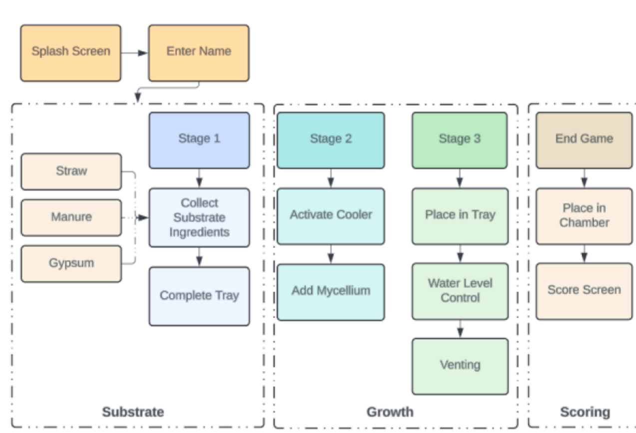

Fig. 1. Game play overview.

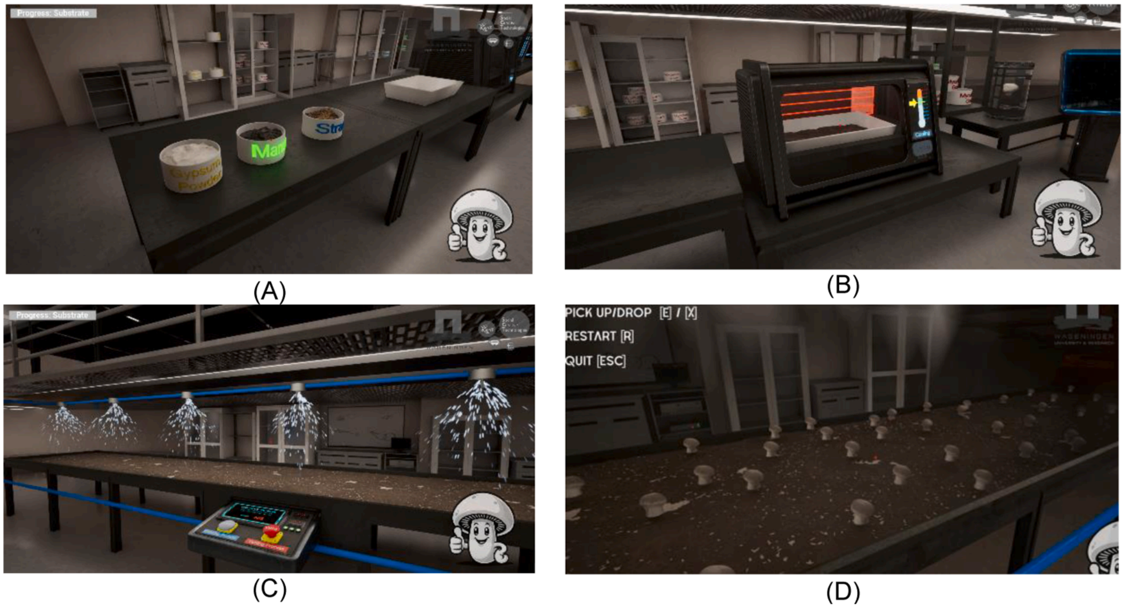

Fig. 2. (A) Substrate mixture, (B) cooling unit, (C) watering station and (D) mushroom growth.

Table 1
Avatar Support.

Avatar Text Support
- Button mushroom substrate is comprised of straw, manure (for composting and additional nitrogen) and a small amount of gypsum;
- The substrate heats up and should be maintained at 80°. For button mushroom compost there is also a second temperature phase of about 40C, where a thermophilic flora develops and further converts the substrate;
- For growing of exotic mushrooms in substrate (when in blocks, bottles, etc.) the substrate is not vented, but the climate room is vented to control temperature;
- Watering should be done before growth of the mushrooms, so that the growing mycelium is not disturbed very much;
- For several species other than button mushrooms watering or misting during their growth is not a problem;

Fig. 3. (A) Score screen (B) mushroom museum.

knowledge for growth, leading to the potential research question of: *Is game-based learning for mushroom cultivation more efficient (*e.g.*, time and money-based) than traditional methods (*i.e.*, book, video-based)*?

Further, as the game is developed in a game engine, there are extension possibilities for the integration of an API [16] connected to real time sensors that link to existing mushroom facilities, whereby the mushroom growth can be based on existing growth conditions rather than in a simulated format, as investigated in agricultural studies using game engines for digital twin applications [17]. This leads to a potential research question of: *How can the integration of real-time sensor data via APIs into game engines enhance the accuracy and applicability of digital twin models for mushroom growth in agricultural simulations*?

5.1. Alpha evaluation

To demonstrate the application examples, we conducted a stakeholder engagement, involving an Alpha testing at the 9th F&A NEXT Summit at Wageningen University [18]. For the testing, questions were developed based on prior investigations [17] into the use of proof of concepts for agricultural games. Table 2, shows that the test group ($n = 10$) were particularly positive about the education potential of the application. The lowest scoring feedback was related to both the technical performance (4.86) and industry (4.86), where the players were asked to grade the response time and interaction, and if they would consider paying for such an application as a learning aid. The main suggestions for further development are presented in Table 3. We identify that a limitation of the Alpha test is the low statistical power, however as Chung et al. [19] outline, for an empirical assessment, 5–25 samples are considered sufficient, and for usability testing, 80 % of issues can be found by 5 testers [19].

Concerning the impact, we outline the following potential use cases and future directions for the DigiFungi software in Table 4 based on the

Table 2
Alpha testing feedback.

Evaluation criteria	Question	Average score*
User-Friendly	Could you validate the application in terms of user experience?	5.14
Complete	To what extent does the application communicate the production phases for white button mushroom production?	5.29
Practical	How recognizable is the application environment?	5.29
Technical Performance	Could you validate the application's response time and interaction?	4.86
Inspiring	To what extent does the application inspire future innovation for mushroom education?	5.71
Educational	To what extent do you think gamification can have an added value in mushroom education and knowledge capture and transfer?	6.43
Industry	I would consider paying to use applications such as DigiFungi as learning aids (1 not all - 7 very much so)	4.86

* (1 poor 7 excellent $n = 7$).

Table 3
Suggestions for future developments.

Question	Response
Do you have any further comments or feedback about the application (positive and negative comments are equally welcome)?	*'Important for learning is detailed feedback. An explanation on why a certain temperature, humidity and venting moment are essential would help people to learn.'* *'Maybe use the museum, like people have to go there first to collect information on growing and then start to try it themselves.'* *'The gamification makes it easier to remember things, repetition that is crucial in learning will be less necessary when you have this visual learning experience.'* *'Good for the user to see some guidelines about the environment and the process. they can be a short tutorial or step-by-step guidelines. For whom that does not have any experiments regarding the mushroom process, these guidelines can be helpful.'*

findings from the aforementioned structured interview process conducted prior to the development of the game; with potential impact points linked to specific Sustainable Development Goals (SDG) [20], clarified within the Benefit category.

Table 4
Potential use cases for DigiFungi.

Use Case	Benefit	Limitations
Workforce Training and General Education	The knowledge abstraction, provided in a digital storytelling implemented in a virtual environment, offers potential for kinaesthetic learning. In other words, catering towards a learn-by-doing approach, linked to SDG4 (quality education). Learning potential could be measured by means of pre- and post-game knowledge tests or evaluating users' ability to apply the learned concepts.	Abstraction of knowledge is also a limitation of the application, as detailed stages of produced are omitted. Further, the current language of the game is English, which does not cater for a wider user base.
Digital Twinning	Connect to real-time IoT sensors using API, for real time growth management. Linked to SDG2 (zero hunger) and SDG3 (good health and wellbeing).	Requires editing the application to link the mushroom morph target growth to align to real time sensor readings by use of an API to real time IoT sensors.
AI Integration	The mushroom avatar within the game, caters for the integration with large language model-based AI applications to display mushroom facts and help the player learn how to grow.	The AI would rely on a third-party large language model and control over the trained AI can be a restriction.
Protein Transition	The game has the potential links to supporting knowledge and understanding of alternative food sources, particularly beyond a protein-based diet linking to SDG11 (sustainable cities and communities), SDG12 (responsible consumption and production) and SDG13 (climate action).	DigiFungi only covers one type of mushroom, which is a significant limitation for food replacement communication.

6. Conclusions

This article documents the software DigiFungi designed to support the teaching of the stages of button mushroom production, but with potential implementation for digital twinning. DigiFungi is used in the Corporate Value Creation-funded project titled '*Towards a Digital Twin and Stackable Growing Pod for Mushrooms*' at Wageningen University and Research (project number: 2,100,987,500). The software was developed as a tool to gamify a complex process and meant to act as an introductory level to button mushroom cultivation for industry-based growers and educators. The knowledge present within the game play is an abstraction of what is by large a significantly complex process. When Alpha-testing the application, users found the game inspiring (5.71) and educational (6.43); however, with room for improvement regarding the technical performance (4.86) and commercial (4.86) benefits. Immediate future directions for this software could involve 1) integration of an API to cater for digital twin applications and 2) optimisation of the environment for better accessibility. Further, users could alter cultivation processes within the game to add further complexities (e.g., harvest challenges).

CRediT authorship contribution statement

William Hurst: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Orestis Spyrou:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Arend F. van Peer:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Reda Simbelyte:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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