Fungateria

Deliverable 6.1/v.1

Portfolio of ELM designs as digital models

Project Number: 101071145

Project Acronym: FUNGATERIA

Project title: Enlisting synthetic fungal-bacteria consortia to produce multi-cellular mycelium-based ELMs with computational capability

Project start: 01 November 2022

Project duration: 48 months

European Innovation Council

Fungateria

DELIVERABLE FACTSHEET

Project Acronym | Number		FUNGATERIA | 101071145	
Deliverable Title:	Portfolio of ELM designs as digital models		
Deliverable Description:	Portfolio of digital designs for ELM morphologies informed by data on qualitative and quantitative parameters such as anticipated biomass generation, distribution and type of functionalities, computational capabilities and morphological development.		
Keywords:	**ELM designs, modelling**		
Due Date:	31.10.2024	**Date of submission:**	30.10.2024
Month of Project:	M24	**Version/Status:**	v1
Dissemination level:	PU	**Dissemination type:**	Other
Report leader:	KADK	**Related WP task:**	WP6, T6.1
Editor(s):	KADK		
Partner Contributions:	KADK, VUB, UGENT, UU		
Final review and approval:	KADK		
Document change history			
Date	**Authors**	**Description**	

PROJECT CONSORTIUM

	Name	Short Name	Country
1.	DET KONGELIGE DANSKE KUNSTAKADEMIS SKOLER FOR ARKITEKTUR, DESIGN OG KONSERVERING	KADK	DK
2.	VRIJE UNIVERSITEIT BRUSSEL	VUB	BE
3.	UNIVERSITEIT GENT	UGent	BE
4.	UNIVERSITEIT UTRECHT	UU	NL
5.	UNIVERSITETET I OSLO	UIO	NO
6.	UNIVERSITY OF THE WEST OF ENGLAND, BRISTOL	UWE	UK
7.	DIMOKRITIO PANEPISTIMIO THRAKIS	DUTH	GR

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

European Innovation Council

Fungateria

EXECUTIVE SUMMARY

This report presents a portfolio of digital ELM designs generated using the ELM modelling framework being developed in WP6. Two design outcomes are investigated. Boundary and initial conditions are defined, and the simulation is then run to yield an outcome. Key parameters of the growth process can be observed during the simulation.

The appendices provide an overview of the model's fundamental relationships between variables in a mycelium cultivation system, and an overview of the causal dependencies between parameters that can be controlled by a designer before and during the cultivation process, and the expected effect of such interventions on the material outcome, locally and by extension globally.

The modelling framework provides the basis for design-evaluate-reiterate loops, but also lays the foundation for generating initial production data for controlling the Growth Composing Platform, which will be the focus of future work.

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

European Innovation Council

Fungateria

TABLE OF CONTENTS

Deliverable factsheet 2
Project Consortium 2
Glossary & Abbreviations ..... **Error! Bookmark not defined.**
Executive Summary 3
1 Introduction 5
2 Design Propositions 5
2.1 ELM Shoe v1(shape, biomass consistency) 6
2.2 ELM Shoe v2 (photomasked shape, biomass consistency) ..... **Error! Bookmark not defined.**
2.3 ELM Shoe v3 (growth media composition, biomass heterogeneity) 7
2.4 ELM indicator (bacterial role) ..... **Error! Bookmark not defined.**
3 Appendix: Model overview 8
3.1 Growth medium composition (petri dish example) ..... **Error! Bookmark not defined.**
3.2 Gas exchange ..... **Error! Bookmark not defined.**
3.3 Temperature 13
3.4 Photonics 14
3.5 Conclusions ..... **Error! Bookmark not defined.**
4 Appendix: Design principles 15
4.1 Surface cultivation (2D) 16
4.2 Photomasking 17
4.3 Volume cultivation (3D) 18
4.4 Occlusion 19
4.5 Conclusions ..... **Error! Bookmark not defined.**

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

European Innovation Council

Fungateria

1 Introduction

Our key objective is to develop a modelling framework that facilitates goal-oriented design exploration of ELM morphologies by forming a closed design-evaluate-reiterate loop. This workflow implies informed decision-making founded on prompt feedback from anticipated qualitative and quantitative data by which the relative qualities of a design can be evaluated, including design target parameters such as biomass generation, material and functional properties and computational capabilities.

With the dynamical system of an ELM-cultivation scenario, design reiteration does not only imply a refinement of the design target, but also the reformulation of an execution strategy detailing how to setup and implement the cultivation conditions so as to arrive as close as possible to the target on a controlled trajectory from the initial conditions. To realise this objective the fundamental task is to describe the evolution of the system with emphasis on the major control parameters by which a designer can intervene in the ELM cultivation process, thereby steering the system towards preferable states.

In the following, we demonstrate the fundamental capacities of our modelling framework with two designs, based on our current design motif of a shoe. The shoe, as a placeholder design target, was described in the scope of works. Its utility lies in the fact that it spans a range of design requirements across functional and aesthetic domains, and as an everyday object is immediately recognisable and relatable in comparison to the other targeted use-case scenarios of the project.

2 Design Propositions

Taken together the two realised designs display a range of the design strategies that can be enacted within, and informed by, the modelling framework. The first design illustrates a cultivation process within a freeform surface where the growth substrate (in this case a porous material) is allowed to fill the volume so as to produce a solid object of graded density when bound by hyphal fibres. The surface is treated as a boundary condition that is gas-permeable while presenting an impassable barrier to hyphal propagation.

The second design shows the synthesis of several design principles in a more complex scenario. Here the shoe is an inert region of space (ceramic volume) covered by a thin layer of growth substrate (such as an agarose gel). Mycelium propagates around the inert region forming a sheet like surface. A UV-light mask further limits the hyphal propagation over the domain, effectively producing holes that connect with the hollow volume of the inert zone. The result is a complex topology with thickness and density varying across the cultivated object.

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

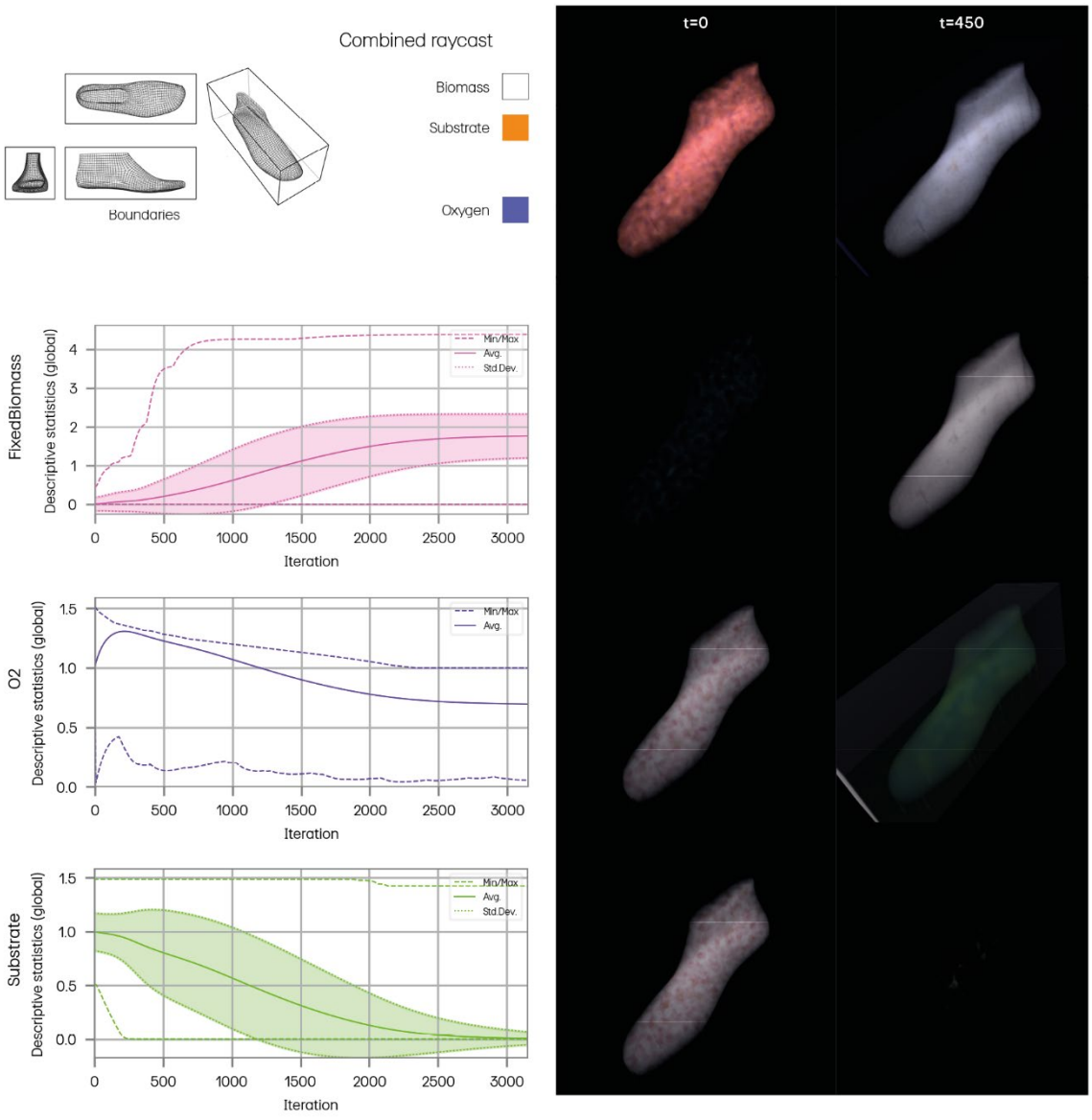
Co-funded by the European Union

European Innovation Council

Fungateria

2.1 ELM Shoe v1(shape, biomass consistency)

SUMMARY	REFERENCES	NOTES
• A forming mould is filled with inoculated wood particle substrate. • Moderate particle size allows gas diffusion in porous matrix, in compromise with final density of mycelium composite material. • The surface of the forming mould is permeable to gases but not hypha, constraining the growth to the boundary volume.		



The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

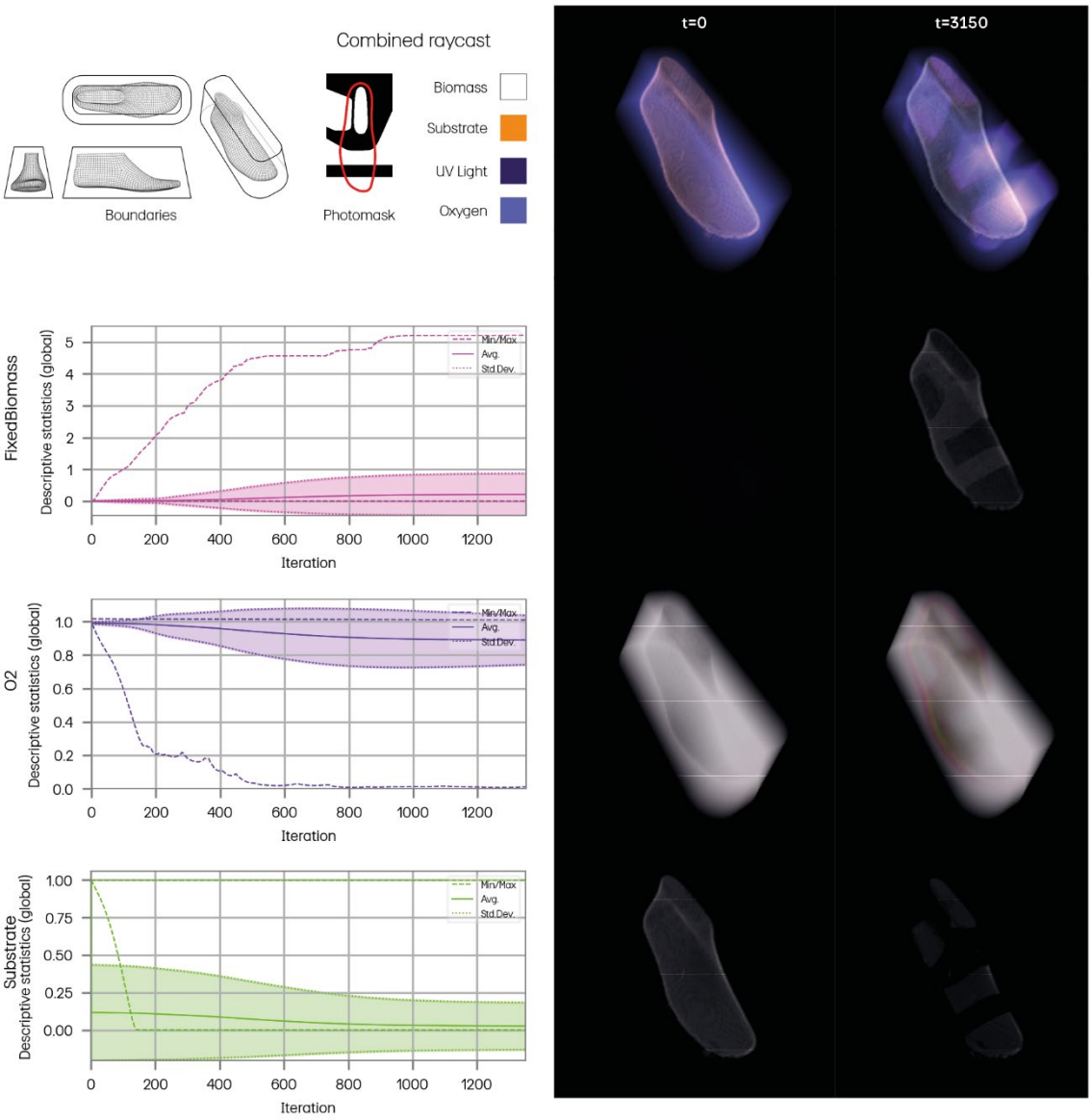
Co-funded by the European Union

European Innovation Council

Fungateria

2.2 ELM Shoe v2 (photomasked shape, biomass consistency)

SUMMARY	REFERENCES	NOTES
• Inert volume inside the forming mould for hollow space. • Mycelium inoculated on agar gel substrate stratum coating the inert volume. • Photomasking prevents growth in certain regions. • Transmittance of agar gel lets the light mask cut all the way down to the inert volume.		



The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

European Innovation Council

Fungateria

2.3 Conclusion

The designs presented above demonstrate a well-developed modelling framework that achieves the ability to define geometries and complementary boundary conditions that represent the physical conditions the model aims to predict. The model captures the causal interdependencies between the fundamental variables of the system and is able to track, analyse, report, and visualize their evolution over the spatial domain in time, letting us monitor key parameters for growth during the cultivation process.

The variables and parameters of the model relate to a number of the control parameters considered for the Growth Composing Platform (GCP), so that there is a congruency between the physical capacities of the bioreactor and the representational and predictive capacities of the model.

Having produced these archetypal designs, we can move towards designs that realise more specific design objectives, targeting built environment use cases, for example, an ELM pollutant indicator and an ELM remediator.

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

European Innovation Council

Fungateria

3 Appendix:

3.1 Model overview

This section presents the fundamental relationships between variables in a mycelium cultivation system to create an overview of the causal dependencies between parameters that can be controlled by a designer before and during the cultivation process and the expected effect of such interventions on the material outcome, locally and by extension globally.

For the sake of intuition, the variable relationships are (mostly) described and illustrated as phenomena in one dimensional space, but principles extend also to 2D and 3D systems.
In general, illustrations have been ordered causally, from top to bottom.

The system described is a high-dimensional multi-physics problem, so simplifications are made here in the name of parsimony. As a dynamical system, it is notable that some parameters may not directly predict the final local outcomes, but directly affect the temporal or spatial evolution of the system locally. Such dependencies can be exploited in goal-oriented design strategies by combining knowledge of spatial distributions over time, with timed and targeted control interventions.

More specifically, a designer can exert influence during the cultivation process by modulating the values of control parameters. Modulation is enacted by fixing values at discrete boundaries, which establishes a 3D field as the effect of the boundary value propagates through the cultivation domain. A sufficiently localised field can be considered a point intervention, and conversely, a sufficiently homogenised field (accomplished for example by mixing) may be thought of as a global intervention. Interventions can also be localised in time (e.g. a pulse), but it is usually more conducive to control to establish a field that persists in time so that it can be mapped to the final spatial distribution of some design target. With multiple fixed boundary conditions, we can establish persistent steady state fields. With fields that change shape over time it is essential to time interventions appropriately with regard to system evolution.

Except for static carbon sources, the fundamental variables of our system all display transport terms. Consequentially, geometry – if taken as a control variable – is the most central dependency of the system. This presents an opportunity to enact overarching control over material outcomes simply by spatial arrangement, but also a challenge as strategies need to be devised to disentangle and counter the effects of geometry where the geometry is itself a fixed design target and cannot be considered a control variable.

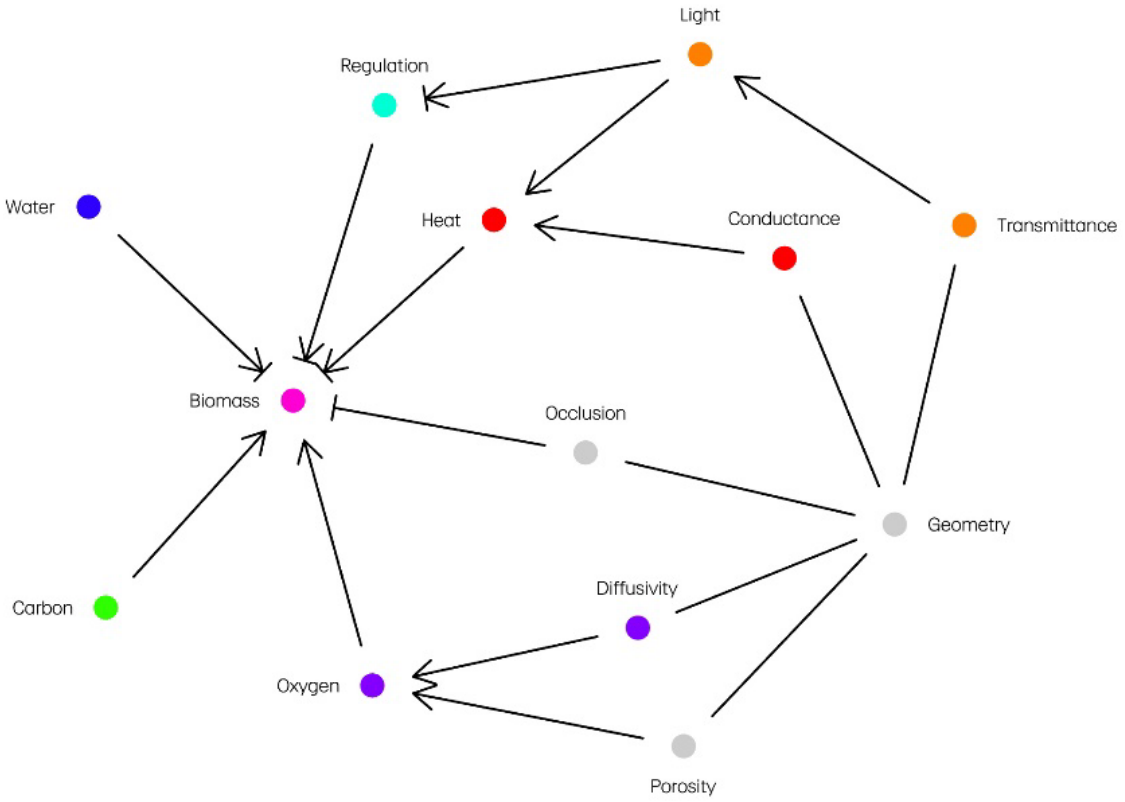
Model formulation is the internalisation of our working assumptions to make predictions. Insofar as these predictions are testable, the model becomes a guide for experimentation that serves to improve the underlying assumptions, in a hypothesise-model-experiment-reiterate loop.

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

European Innovation Council

Fungateria



Simplified causal graph of cultivation system

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

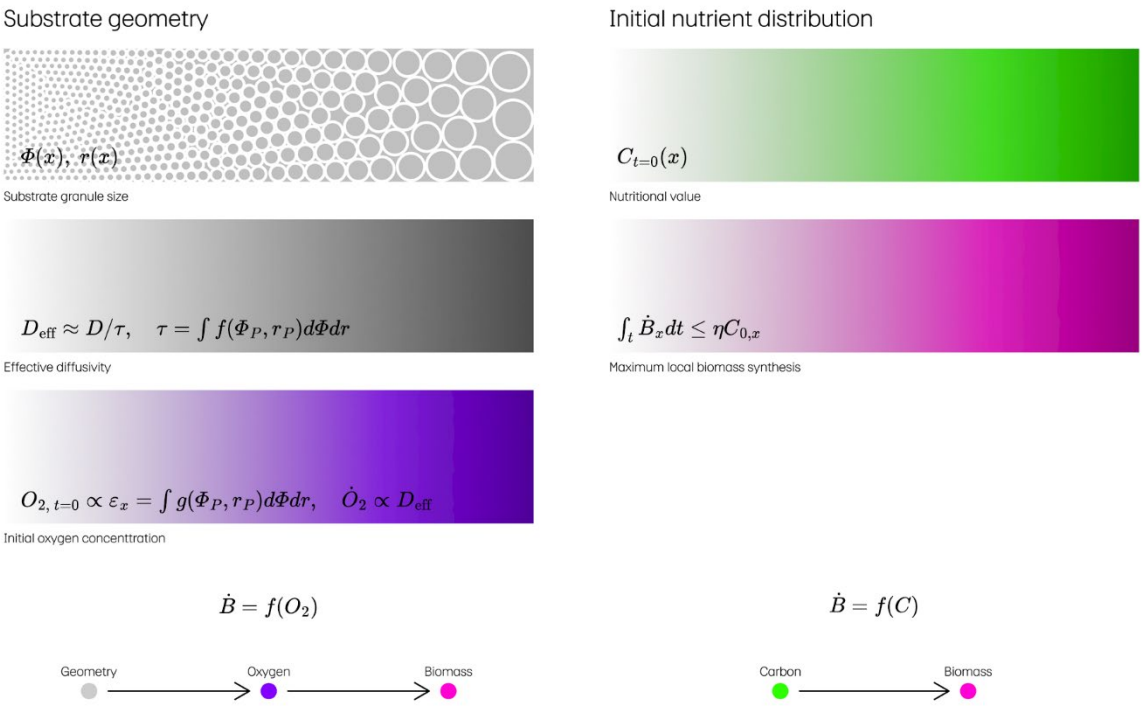
Co-funded by the European Union

European Innovation Council

Fungateria

3.1.1 Biomass

SUMMARY	REFERENCES	NOTES
• The biomass produced locally is a (metabolic) function of the growth substrate composition. Material grading can be achieved by directly modulating the distribution of nutrients at the time of inoculation. • Substrate shape and granularity influences the geometry of the pore space. The rate of gas exchange can thus be modulated by substrate mix, limiting or facilitating respiration.		Φ : Sphericity r : Radius τ : Tortuosity D : Diffusivity ε : Porosity Ω : Surface B : $Biomass$ O_2 : $Oxygen$ P : $Particles$ C : Nutrients (Carbon) η : Conversion efficiency



The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

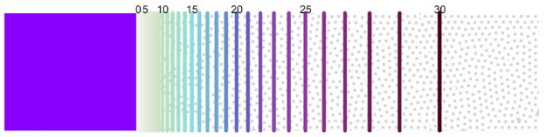
European Innovation Council

Fungateria

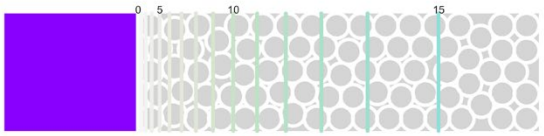
3.1.2 Aeration

SUMMARY	REFERENCES	NOTES
• Oxygen is essential for biomass production. Spatial grading can be achieved by controlling access to oxygen through gas exchange. • Gas concentrations equilibrate over time by diffusion, so timing of growth can be controlled by oxygen source for temporal grading. • Oxygen access can be controlled globally with fans, and locally by pore geometry. • Pores can be built into the substrate structure (e.g. including straw in growth medium) or be modulated by changing substrate grain size (in SSF).		D_{eff}: Effective diffusivity Ω : Volume set $\partial\Omega$: Surface set of Ω ξ : Point in $\partial\Omega$ ∇: Gradient ∇^2: Laplacian C : Constant O_2: Oxygen

Temporal grading



Low gas exchange → Slow temporal progression



High gas exchange → Faster temporal progression

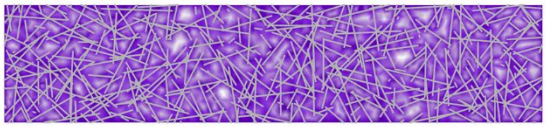
$$D_{\text{eff},x} = f(\Omega_{\text{substrate}})$$

$$\dot{O}_{2,x} = -D_{\text{eff},x}\nabla^2 O_2$$

$$\nabla O_{2,\text{steady state}} = C$$

$$\nabla^2 O_{2,\text{steady state}} = 0$$

Structural respiration

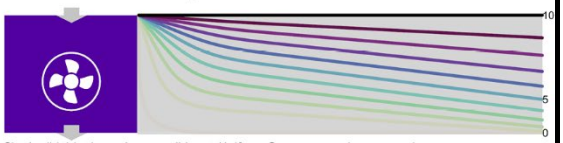


Unstructured respiratory airways → Homogeneous O_2 transport (effective diffusivity)

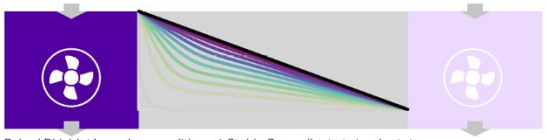
Structured respiratory airways → Graded O_2 delivery

$$O_{2,x,t} = \int_{\Omega} f(||x - \xi||)d\xi$$

Ventilation strategies



Single dirichlet boundary condition → Uniform O_2 concentration at steady state



Paired Dirichlet boundary conditions → Stable O_2 gradient at steady state

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

European Innovation Council

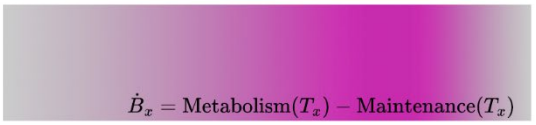
Fungateria

3.1.3 Temperature

SUMMARY	REFERENCES	NOTES
• Temperature influences the overall metabolic rate. The rate of biomass can be controlled both locally and globally by modulating temperature. • Temperature can be controlled locally with heat sources and lights. • Temperature can be controlled globally by changing with the bioreactor, or as a gradient with a heat source and sink. • By controlling the heat conductance of the growth medium, we can control the curvature of temperature gradients.		α : Thermal diffusivity Ω : Volume set $\partial\Omega$: Surface set of Ω ξ : Point in $\partial\Omega$ ∇: Gradient ∇^2: Laplacian T : Temperature B : Biomass O_2: Oxygen C : Constant

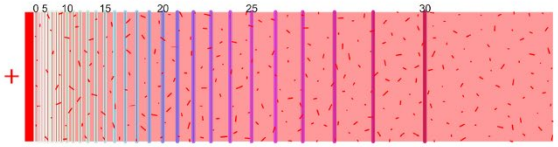
Temperature vs Biomass

Temperature gradient

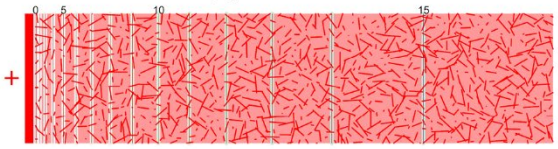


Metabolic activity (growth rate)

Temporal grading



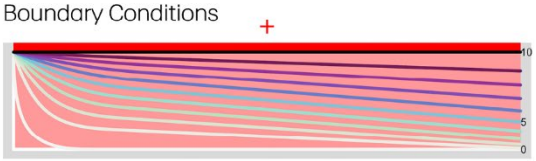
Low heat conductance → Slower progression



High heat conductance → Faster progression

$$\dot{T}_x = -\alpha_x \nabla^2 T$$

Boundary Conditions

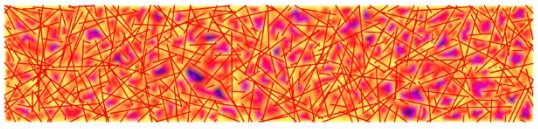


Single dirichlet boundary condition → Uniform O_2 concentration at steady state

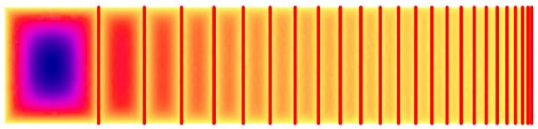
Paired Dirichlet boundary conditions → Stable temperature gradient at steady state

$$\nabla^2 T_{\text{steady state}} = 0$$
$$\nabla T_{\text{steady state}} = C$$

Structural heat conductance



Unstructured heat conductance → Uniform temperature at steady state



Structured heat conductance → Graded temperature distribution

$$T_{x,t} = \int_{\Omega} f(||x - \xi||) d\xi$$

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

European Innovation Council

Fungateria

3.1.4 Photonics

SUMMARY	REFERENCES	NOTES
• Light can be used to trigger cell signaling cascades, allowing the engineering of mappings from wavelength specific behavioral responses. • Light can be used as a highly localised heat source, affecting the overall metabolic rate. • High-intensity light can be used to increase cell maintenance costs, slowing or arresting growth. • By controlling the transmittance of the growth substrate, the depth of the light stimulus can be controlled.		I_y : Intensity at depth y μ : Absorption coefficient I_λ : I of wavelength λ P : Spectral distribution Q : Heat load

Transmittance

Medium transmittance (opacity)

Light penetration (remaining intensity after absorption)

Photogenic heat load

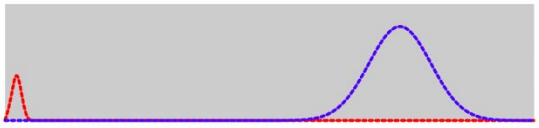
Local light absorption

Heat load

Wavelength

Spectral power distribution

$$I_{\lambda,x} = P(\lambda, x) = f(x)$$



Photosensory response

$$\text{Sensory response}_x = f\left(\int_\lambda I_\lambda d\lambda\right)$$

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

European Innovation Council

Fungateria

3.2 Appendix: Design Principles

The low-level description of the system above makes it is possible to formulate design strategies based on system behavior that follows from the predictions of the model under the current assumptions. Some of these design principles are put forth in the following section.

These principles are (mostly) described and illustrated as phenomena in two-dimensional space but extend also to 3D systems. In general, illustrations have been ordered causally, from top to bottom.

Of special note is the strategic potential of transport phenomena in allowing spatial grading of design targets without complex interventions but instead requiring a higher degree of temporal precision during the cultivation process.

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

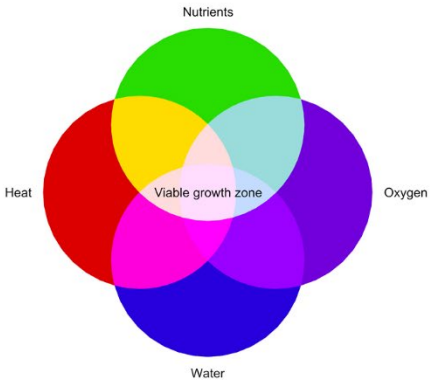
European Innovation Council

Fungateria

3.2.1 Surface cultivation (2D)

SUMMARY	REFERENCES	NOTES
• The mycelium can be cultivated as a thin surface by limiting the access to necessary substrate components to the surface. • Density of the growth substrate will influence oxygenation. For example, in agar gel oxygen diffusion is limited, so that mycelium cannot penetrate far below the gel gas interface even though there is plenty of organic carbon throughout.		Ω : Volume set C : Nutrients (Carbon) O_2: Oxygen H_2O : Water T : Temperature B : Biomass

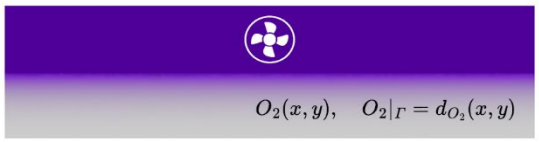
Viable Growth Zone



$$\begin{cases} \Omega_{T,viable} & = \{(x,y) \in \Omega \mid T_{\text{crit},-} < T < T_{\text{crit},+}\} \\ \Omega_{C,viable} & = \{(x,y) \in \Omega \mid C_{\text{crit}} < C\} \\ \Omega_{H_2O,viable} & = \{(x,y) \in \Omega \mid H_2O_{\text{crit},-} < H_2O < H_2O_{\text{crit},+}\} \\ \Omega_{O_2,viable} & = \{(x,y) \in \Omega \mid O_{2,\text{crit}} < O_2\} \\ \\ \Omega_{B,viable} & = \Omega_{T,viable} \cap \Omega_{C,viable} \cap \Omega_{H_2O,viable} \cap \Omega_{O_2,viable} \end{cases}$$

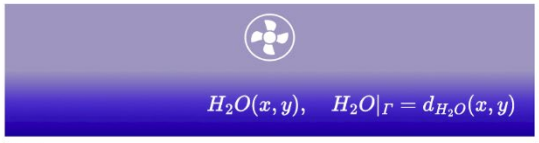
Nutrients

Combined viability



Oxygen

Biomass



Water

Heat

$$\begin{cases} \dot{B} = f(C, O_2, H_2O, T) > 0 & \text{for} \quad (x,y) \in \Omega_{B,viable} \\ \dot{B} = 0 & \text{for} \quad (x,y) \notin \Omega_{B,viable} \end{cases}$$

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

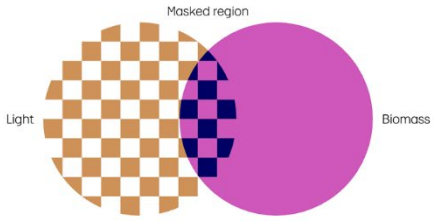
European Innovation Council

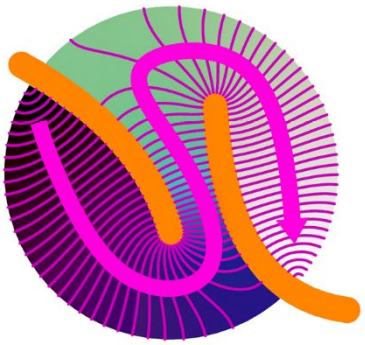
Fungateria

3.2.2 Photomasking

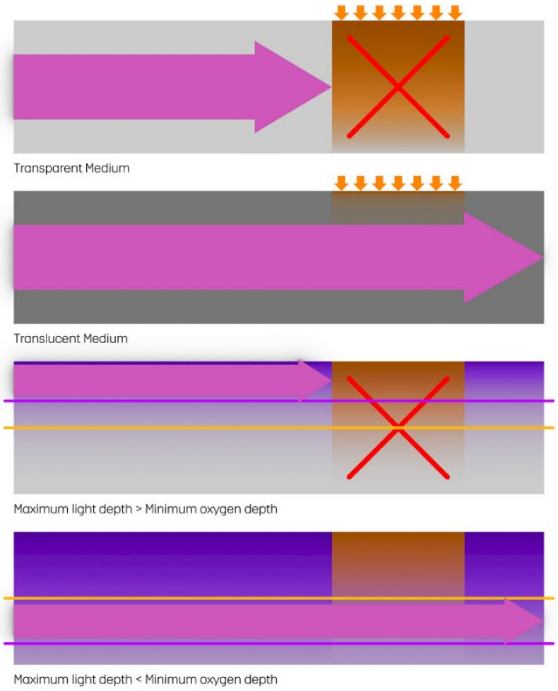
SUMMARY	REFERENCES	NOTES
• Local modulation of surface growth can be achieved by restricting light stimuli to specific regions by masking. • Depending on the transmittance of the substrate, the depth of the penetrating light can hinder the mycelium from propagating through a region under the surface (gas interface). • Regions can be opened and closed to mycelium propagation sequentially.		$\partial\Omega$: Surface set of Ω Γ : Subset of $\partial\Omega$ I_λ : I of wavelength λ $\lvert\vec{v}\rvert$: Propagation speed O_2 : Oxygen D_{eff} : Effective diffusivity I_0 : Surface intensity μ : Absorption coefficient z : Depth

Photomasking





Propagation over surface with light obstructions



$$\begin{cases} \Gamma_{\text{mask}} = \{(x,y,z) \in \partial\Omega \mid I_\lambda(x,y,z) > I_{\lambda,\text{crit}}\} \\ \Gamma_{B,viable} = \Gamma_{\text{mask}} \cap \Omega_{B,viable} \end{cases}$$

$$\begin{cases} |\vec{v}_{B,z}| > 0 \quad \text{for} \quad z > z_{\text{crit}} \\ |\vec{v}_{B,z}| = 0 \quad \text{for} \quad z \leq z_{\text{crit}} \end{cases}$$

$$z_{\text{crit}} = f(O_2, D_{\text{eff},O_2}, I_0, \mu)$$

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

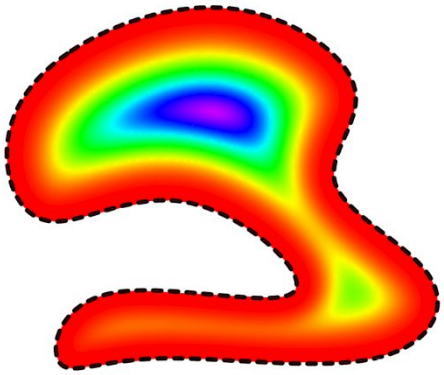
European Innovation Council

Fungateria

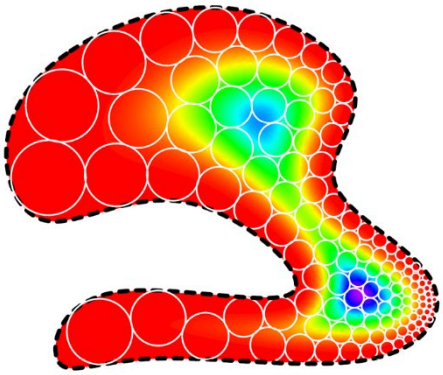
3.2.3 Volume cultivation (3D)

SUMMARY	REFERENCES	NOTES
• Freeform geometries filled with inoculated substrate. • Local biomass growth will depend on access to oxygen, leading areas further away from the gas phase medium to develop more slowly. • Locally altering the oxygen permeability of the boundary surface changes the volumetric biomass gradient. • Respiratory structures within the volume can improve oxygenation.		$\partial\Omega$: Surface of Ω P : Point in Ω ξ : Point on $\partial\Omega$ μ : Diffusive substance

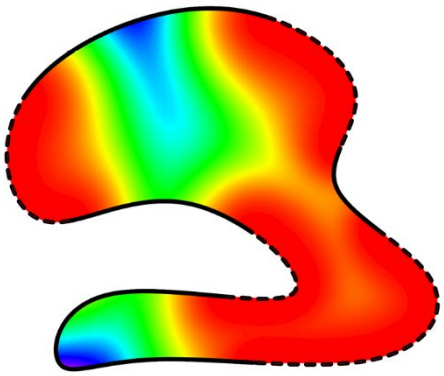
Volume cultivation



Gas-permeable boundary



Variable subtrate conductance



Aeration with gaseous diffusion barriers

$$u_{x,y,z} = \int_{\partial\Omega} f(||P_{x,y,z} - \xi||)d\xi$$

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

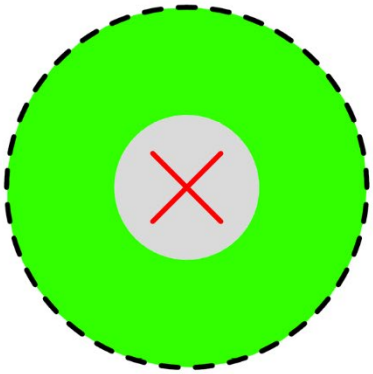
European Innovation Council

Fungateria

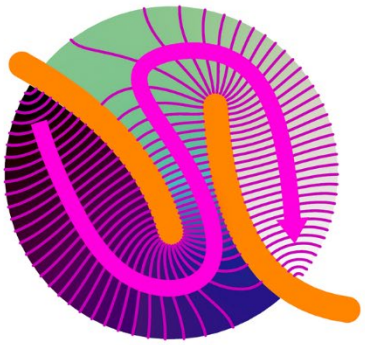
3.2.4 Occlusion

SUMMARY	REFERENCES	NOTES
• Materials that are inert relative to the organism (e.g. ceramics, plastics) can be used to create negative spaces inside a volume. • These can also be applied as obstacles to control propagation as a sequence. • Materials that are inert to the organism can still participate in other transport phenomena, e.g. heat conductance.		

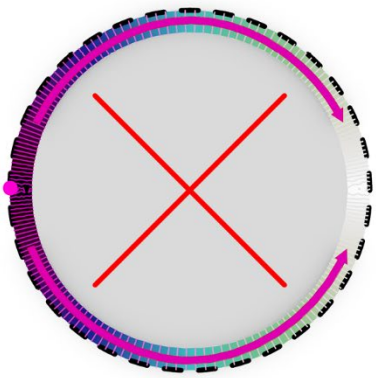
Inert occlusion



Occlusion by inert geometry



Propagation over surface with light obstructions



Propagation around occluded zone from inoculation point

The FUNGATERIA project has received funding from the European Union's HORIZON-EIC-2021-PATHFINDER CHALLENGES programme under grant agreement No. 101071145

Co-funded by the European Union

European Innovation Council