Modeling and simulating the MELiSSA loop to understand the effects of system interaction on survivability during long-duration interstellar missions: an agent-based approach

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TPM, Room B1.300

Period: from Q3 till Q4-2017
More info: Angelo Vermeulen, a.c.j.vermeulen@tudelft.nl
Evolvable Spacecraft

Active Component

Passive Component

Environmental Changes

Internal Changes

Raw Materials

Bootstrapping Growth and Evolution
ASTEROID MINING
3D PRINTED MODULAR ARCHITECTURE
Modeling by Nils Faber
EVOLUTION

REGENERATIVE Ecosystem

ASTEROID

RESOURCES

GROWTH

ARCHITECTURE

ENVIRONMENTAL IMPACT

MODEL DEVELOPMENT

EVOLUTION
MODEL DEVELOPMENT

ASTEROID

RESOURCES

REGENERATIVE ECOSYSTEM

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REGENERATIVE ECOSYSTEM
AGENT-BASED MODELING

DEFINITION

• Works with agents and ticks
• Focus on interactions and emergent patterns
• High granularity and ontological correspondence
Bacterial Protein
Fecal Protein
Lipids
Polysaccharides
Food biomass
VFAs
HNO₃
NH₃
CO₂
H₂O
H₂
O₂

IVa
IVb

V

III

I

II

Compartment
Reservoir
Auxiliary process

MELiSSA MASS FLOWS

H₂+O₂→H₂O
ASSUMPTIONS & ADDITIONS

• 12 reservoirs
• 1 auxiliary process: hydrogen oxidization
• Surplus biomass of Compartment II goes to Compartment I
• 3 biomass formulas: edible + non-edible + Rhodospirillum
• 2 protein formulas: plant/algae/feces + Rhodospirillum
COMPARTMENT I

Fecal protein
$3,2\text{CH}_{1.76}\text{O}_{0.239}\text{N}_{0.239} + 3,035\text{H}_2\text{O} = \text{C}_2\text{H}_4\text{O}_2 + 0.1\text{C}_4\text{H}_8\text{O}_2 + 2.3\text{H}_2 + 0.76\text{NH}_3 + 0.8\text{CO}_2$

Bacterial protein
$3,2\text{CH}_{1.4697}\text{O}_{0.34}\text{N}_{0.2807} + 2,712\text{H}_2\text{O} = \text{C}_2\text{H}_4\text{O}_2 + 0.1\text{C}_4\text{H}_8\text{O}_2 + 1,3162\text{H}_2 + 0.8982\text{NH}_3 + 0.8\text{CO}_2$

Polysaccharides
$3,199\text{CH}_{1.667}\text{O}_{0.833} + 1,134\text{H}_2\text{O} = \text{C}_2\text{H}_4\text{O}_2 + 0.1\text{C}_4\text{H}_8\text{O}_2 + 1.4\text{H}_2 + 0.8\text{CO}_2$

Lipids
$\text{C}_{16}\text{H}_{32}\text{O}_2 + 13,0278\text{H}_2\text{O} = 6,5278\text{C}_2\text{H}_4\text{O}_2 + 0.6528\text{C}_4\text{H}_8\text{O}_2 + 0.3333\text{CO}_2 + 13.3611\text{H}_2$
COMPARTMENT I

Fecal protein
3,2CH\textsubscript{1.76}O\textsubscript{0.239}N\textsubscript{0.239} + 3,035H\textsubscript{2}O = C\textsubscript{2}H\textsubscript{4}O\textsubscript{2} + 0,1C\textsubscript{4}H\textsubscript{8}O\textsubscript{2} + 2.3H\textsubscript{2} + 0.76NH\textsubscript{3} + 0,8CO\textsubscript{2}

Bacterial protein
3,2CH\textsubscript{1.4697}O\textsubscript{0.34}N\textsubscript{0.2807} + 2,712H\textsubscript{2}O = C\textsubscript{2}H\textsubscript{4}O\textsubscript{2} + 0,1C\textsubscript{4}H\textsubscript{8}O\textsubscript{2} + 1,3162H\textsubscript{2} + 0.8982NH\textsubscript{3} + 0,8CO\textsubscript{2}

Polysaccharides
3,199CH\textsubscript{1.667}O\textsubscript{0.833} + 1,134H\textsubscript{2}O = 1C\textsubscript{2}H\textsubscript{4}O\textsubscript{2} + 0,1C\textsubscript{4}H\textsubscript{8}O\textsubscript{2} + 1,4H\textsubscript{2} + 0,8CO\textsubscript{2}

Lipids
C\textsubscript{16}H\textsubscript{32}O\textsubscript{2} + 13,0278H\textsubscript{2}O = 6,5278C\textsubscript{2}H\textsubscript{4}O\textsubscript{2} + 0,6528C\textsubscript{4}H\textsubscript{8}O\textsubscript{2} + 0,3333CO\textsubscript{2} + 13,3611H\textsubscript{2}
COMPARTMENT I

Fecal protein
\[3,2\text{CH}_{1.76}\text{O}_{0.239}\text{N}_{0.239} + 3,035\text{H}_2\text{O} = \text{C}_2\text{H}_4\text{O}_2 + 0,1\text{C}_4\text{H}_8\text{O}_2 + 2.3\text{H}_2 + 0.76\text{NH}_3 + 0,8\text{CO}_2\]

Bacterial protein
\[3,2\text{CH}_{1.4697}\text{O}_{0.34}\text{N}_{0.2807} + 2,712\text{H}_2\text{O} = \text{C}_2\text{H}_4\text{O}_2 + 0,1\text{C}_4\text{H}_8\text{O}_2 + 1,3162\text{H}_2 + 0.8982\text{NH}_3 + 0,8\text{CO}_2\]

Polysaccharides
\[3,199\text{CH}_{1.667}\text{O}_{0.833} + 1,134\text{H}_2\text{O} = 1\text{C}_2\text{H}_4\text{O}_2 + 0,1\text{C}_4\text{H}_8\text{O}_2 + 1,4\text{H}_2 + 0,8\text{CO}_2\]

Lipids
\[\text{C}_{16}\text{H}_{32}\text{O}_2 + 13,0278\text{H}_2\text{O} = 6,5278\text{C}_2\text{H}_4\text{O}_2 + 0,6528\text{C}_4\text{H}_8\text{O}_2 + 0,3333\text{CO}_2 + 13,3611\text{H}_2\]
COMPARTMENT I

Fecal protein
$$3.2\text{CH}_{1.76}\text{O}_{0.239}\text{N}_{0.239} + 3.035\text{H}_2\text{O} = \text{C}_2\text{H}_4\text{O}_2 + 0.1\text{C}_4\text{H}_8\text{O}_2 + 2.3\text{H}_2 + 0.76\text{NH}_3 + 0.8\text{CO}_2$$

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Lipids
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<table>
<thead>
<tr>
<th>Compound</th>
<th>Consumed (g)</th>
<th>Produced (g)</th>
<th>Flow conservation</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacterial Protein</td>
<td>13828</td>
<td>13828</td>
<td>100.0%</td>
<td>0.00</td>
</tr>
<tr>
<td>Fecal Protein</td>
<td>1148</td>
<td>1148</td>
<td>100.0%</td>
<td>0.00</td>
</tr>
<tr>
<td>Polysaccharides</td>
<td>7486</td>
<td>7486</td>
<td>100.0%</td>
<td>0.00</td>
</tr>
<tr>
<td>Lipids</td>
<td>1912</td>
<td>1912</td>
<td>100.0%</td>
<td>0.00</td>
</tr>
<tr>
<td>Food - higher plants</td>
<td>3600</td>
<td>3600</td>
<td>100.0%</td>
<td>0.00</td>
</tr>
<tr>
<td>Food - algae</td>
<td>400</td>
<td>400</td>
<td>100.0%</td>
<td>0.00</td>
</tr>
<tr>
<td>Acetate</td>
<td>20501</td>
<td>20501</td>
<td>100.0%</td>
<td>-0.01</td>
</tr>
<tr>
<td>Butyrate</td>
<td>3008</td>
<td>3008</td>
<td>100.0%</td>
<td>-0.01</td>
</tr>
<tr>
<td>HNO₃</td>
<td>2228</td>
<td>2228</td>
<td>100.0%</td>
<td>-0.07</td>
</tr>
<tr>
<td>NH₃</td>
<td>3487</td>
<td>3494</td>
<td>99.8%</td>
<td>6.90</td>
</tr>
<tr>
<td>CO₂</td>
<td>13703</td>
<td>13788</td>
<td>99.4%</td>
<td>85.92</td>
</tr>
<tr>
<td>H₂O</td>
<td>17602</td>
<td>17564</td>
<td>100.2%</td>
<td>-37.95</td>
</tr>
<tr>
<td>O₂</td>
<td>12186</td>
<td>12186</td>
<td>100.0%</td>
<td>0.00</td>
</tr>
<tr>
<td>H₂</td>
<td>1018</td>
<td>1027</td>
<td>99.2%</td>
<td>8.18</td>
</tr>
</tbody>
</table>
PLANT PLOT AGENT

1 AGENT

ATTRIBUTES

• Ideal plant: 100 day growth cycle, 40g dry weight, 60kcal, 0.5 harvest index
• Plant plot agent: 180 plants, 1 plant plot provides enough nutrients for a crew of 6 for 1 day
• 100 day production line: 100 plant plots

BEHAVIOR

Input-output: stoichiometry
**PLANT PLOT AGENT**

**STATES**

- Growth follows a sigmoid curve
- Reaching 40g in 100 days (10% first and 10% last week)
- For each day there’s a specific biomass increase, and hence, the corresponding necessary input can be deduced according to the plant plot’s stoichiometry
GROWTH (BIOMASS)

TIME (DAYS)

REDUCED HARVEST
PLANT PLOT AGENT

GROWTH (BIOMASS)

NO NUTRIENTS

NO HARVEST

TIME (DAYS)
**ATTRIBUTES**

1 bioreactor = 1 agent
Compartments II and IVa create biomass (consumption)
Compartments I and III have no biomass (no consumption)

**BEHAVIOR**

Input-output: stoichiometry
BIOREACTOR AGENT

STATES

- Growth follows a sigmoid curve
- Density reaching 100% in 28 days (10% first and 10% last week)
- 100% density corresponds to a maximum productivity, and hence, a specific amount of nutrients according to the bioreactor’s stoichiometry
- Each < 100% density along the curve requires a proportionally lower amount of nutrients
BIOREACTOR AGENT

GROWTH (DENSITY) vs. TIME (DAYS)
BIOREACTOR AGENT

NUTRITION

DENSITY

100% 100% 100% 80% 90% 100%

80 80 80 80 90 100

100% 100% 100% 80% 90% 100%
<table>
<thead>
<tr>
<th>Compartment</th>
<th>Type</th>
<th>Organism</th>
<th>Productivity</th>
<th>Nutritional value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Bioreactor</td>
<td>Fermenting bact.</td>
<td>6000mg VFAs/L/day*</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Bioreactor</td>
<td>Rhodospirillum</td>
<td>2112mg biomass/L/day*</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Bioreactor</td>
<td>Nitrifying bact.</td>
<td>8740mg nitrates/L/day*</td>
<td></td>
</tr>
<tr>
<td>IVa</td>
<td>Bioreactor</td>
<td>Arthrospira</td>
<td>7990mg biomass/L/day*</td>
<td>6 x 200 kcal</td>
</tr>
<tr>
<td>IVb</td>
<td>Plant plot</td>
<td>Ideal plant</td>
<td>7200g biomass/day†</td>
<td>6 x 1800 kcal</td>
</tr>
<tr>
<td>V</td>
<td>Cap</td>
<td>Crew</td>
<td>350g feces/day†</td>
<td></td>
</tr>
</tbody>
</table>

* Peer-reviewed literature
† Calculated
to eat.human ; defines outputs of CV
  let i 0 ; arbitrary 'large' number
  let ratio 10 ; arbitrary 'large' number
  while [i < length requirements[]]
    let req array:item requirements i
    let ink array:item intake i
    ifelse req = 0
      set i i + 1
    else
      if ink / req < ratio
        set i i + 1
      set ratio ink / req
    [ i i + 1]
  ]

  ifelse ratio < 1
    [while [i > 0]]
      set i i - 1
      array:set intake i (ratio * (array:item requirements i))
      array:set output i (array:item products i / ratio) ; excretes subject to the lowest ingested nutrient
    [while i > 0]
      set i i - 1
      array:set intake i (array:item requirements i)
      array:set output i (array:item products i)
    
    set health 1
  end
CONCLUSIONS

• Abstraction of the MELiSSA system with a stoichiometrically balanced representation of all key mass flows
• This was translated into a working agent-based model (proof of concept stage)
• Agent-based modeling seems a proper tool to perform design research of a complex system such as MELiSSA:
  ▪ individual interactions and network effects
  ▪ ontological correspondence
NEXT STEPS

• Increase the *fidelity* of the model (e.g. crop differentiation, organism-specific growth curves, environmental effects)
• Set up experiments exploring system design principles for maximizing *survivability* in adverse deep space conditions
• Make the model decision making processes *evolvable*
• Connect this model to the *mining-architecture* model of the starship
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