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Novel Interactive Learning Tool for Cleaner Production Studies: Case Study

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***Abstract* – This study introduces a novel interactive learning tool (ILT) designed to enhance the understanding and application of cleaner production principles with a case study in mushroom cultivation waste management. Utilizing a System Dynamics approach, this tool evaluates the socio-economic and environmental impacts of the polysaccharide extraction process from the spent mushroom substrate. The methodology encompasses the use of a model to simulate causal effects within production and supply chains, supported by an interactive interface that has been tested among master's degree students of the Environmental Engineering program. The effectiveness of the tool was assessed through an online survey of 11 environmental engineering master's students at the Riga Technical University. A Bayesian binomial test provided moderate support (BF+0 = 6.086) to the hypothesis that the proportion of students in support of ILT application is greater than 0.5 (95 % CI [0.553, 0.946]).**

***Keywords* – Environmental engineering; quality education; system dynamics; survey.**

1. INTRODUCTION

Along with the rapid development of the mushroom cultivation industry, it is expected that in less than three years, the amount of waste generated from mushroom cultivation may reach even more than 100 million tons [1]. The most significant amount of this waste is the spent mushroom substrate (SMS), since, on average, 5 kg of plant biomass-based substrate is required to produce 1 kg of mushrooms [2]. SMS is underutilized, as it is most often disposed of by burning. However, this widespread practice goes against sustainability principles and results in a considerable waste of biomass resources that are highly valuable to produce other products with high added value [3]. One such promising possibility is the extraction and utilization of polysaccharides [4]. Polysaccharides are essential macromolecules that are widely found in plants. They have significant applications in medicine (anti-cancer, antioxidant properties) [5], [6], food (processing, packaging) [7], cosmetics (anti-aging, moisturizing characteristics) [8], remediation of pollutants (wastewaters), material science, and other fields [9]. In the context of the reuse of mushroom cultivation waste, the extraction of polysaccharides is a sustainable solution that reduces the amount of waste and, accordingly, the impact on the environment and creates economic value [10].

The analysis of the valorization of SMS can be evaluated using mathematical methods. These abstract representations use mathematical language to describe real-world systems'

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behavior, mechanisms, and dynamics [11] and can be used as a decision-support system for policymakers [12]. Mathematical modeling involves constructing models and applying techniques to solve them [13]. These techniques include, but are not limited to, statistical models [14], [15], differential equations, machine learning algorithms, neural network models [16], vector fields [17], numerical analysis [18], and System Dynamics (SD) [19]. The SD is beneficial for highly complex problems [20].

These mathematical models can be further upgraded into decision-making tools where the model serves the role of an engine that calculates outputs based on the user inputs. Decision-making tools are systems or software designed to aid individuals or organizations in making choices by organizing information and evaluating different possibilities [21]. These tools can range from simple techniques to complex software that integrates various data sources and methodologies to provide insights for informed decision-making [22]. Practical decision support tools prioritize stakeholder needs and perspectives and improve decision-making by reducing friction and increasing efficiency in complex decision-making processes [23]. Decision-making tools can be readjusted as interactive learning environments (ILEs) [24] that leverage technology and game design elements to enhance learning experiences [25]. Interactive learning in informal learning can boost creativity and engagement, especially when gamified, leading to improved knowledge acquisition and satisfaction [26].

The United Nations 2030 Agenda for Sustainable Development emphasizes quality education, highlighting digital technologies as key tools in achieving inclusive and equitable education [27]. One such digital technology is Interactive Learning Platforms (ILP) [28]. ILPs have gained increased attention over the years [29]. They are known for improving student learning performance, motivation, and mental health [30] and ILEs could be used as part of ILP. There are existing studies that have applied similar approaches such as using SD in climate policy context [31], virtual laboratories [32], use of virtual reality [33], and experimenting with systems that are dangerous to test in reality [34].

The study aims to develop a novel interactive online learning tool (ILT) for use in Environmental Engineering and Cleaner Production course lessons, specifically tailored to a waste-to-wealth case study of polysaccharide extraction from SMS. The following research questions have been addressed in this study:

– How do students perceive incorporating ILT in their curriculum?
– Do students support the incorporation of ILT in their curriculum?

2. METHODOLOGY

In this study, SD modeling is used. It provides a robust framework for analyzing complex interactions between environmental, economic, and social factors in cleaner production processes. Through SD feedback loops, time delays, and non-linear relationships can be captured, which often lead to unintended consequences over the long term, which other methods can often overlook. Software Stella Architect [35] has been used in modeling due to its convenience and support for interactive interface development. Also, Systems Thinking is incorporated as a holistic approach to understanding behavior, patterns, and cycles rather than specific events in the system [36]. System analysis recognizes connections between system variables, identifies causality loops, and interprets dynamic behavior [37].

In addition to the SD model, an ILT has been developed. Twenty Master of Environmental Engineering students enrolled in a Cleaner Production course have been handed the ILT. A survey with choice and open-ended questions is used to assess the perception of the ILT. The survey was gathered using Google Forms [38] and embedded in the ILT:

https://forms.gle/24bE75zoqBVc2C7x9. The survey has been analyzed using JASP statistical software [39]. The study methodology is available in Fig. 1.

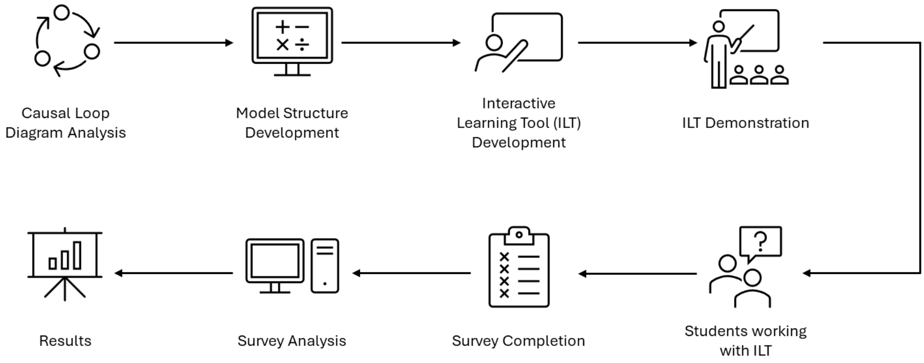

Fig. 1. Study methodology.

2.1. System's Causal Loop Analysis

The causal loop diagrams are incorporated into the analysis to develop the SD model. They are used to understand and communicate the behavior of complex systems [40]. These are useful for locating leverage points that can lead to system behavior changes [41]. Each arrow describes the relationship between two variables. The end of the arrow shows a "+" sign describing a positive interaction or a "–" sign describing a negative interaction [42]. Loops are a chain of arrows through variables, where the last arrow returns to the initial variable from which the arrow comes from [43].

In this model, many interactions between the variables influence the system's behavior. The causal loop diagram shows the most fundamental aspects of the production complexity in Fig. 1.

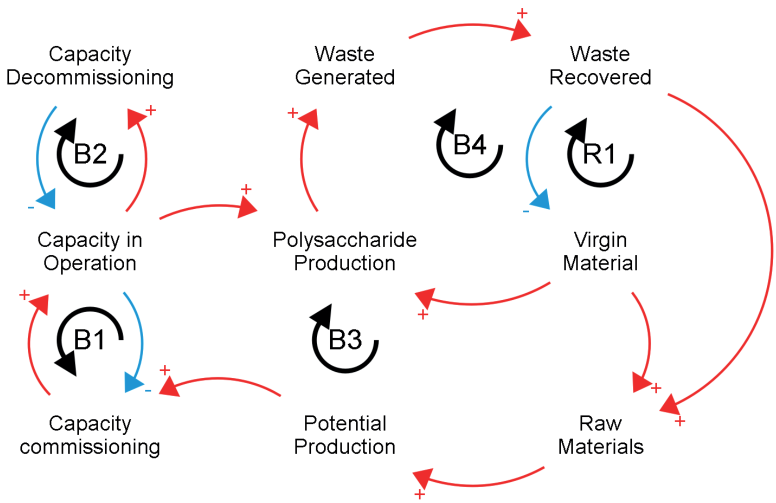

Fig. 1. Causal loop diagram for the SD model.

Balancing loop B1 represents the adjustment of the current capacity in operation, given the change in potential production rate through capacity commissioning. The bigger the difference between potential production and capacity in operation, the more capacity is commissioned. Balancing loop B2 shows aging of production capacity as capacity after reaching its technical lifetime is removed. Balancing loop B3 shows how potential production is adjusted given the amount of waste recovered. The more waste that can be recovered, the less virgin material is needed, and the potential production is therefore decreased. Balancing loop B4 shows how polysaccharide production is adjusted given the waste recovery. The more waste is recovered, the less virgin material, such as SMS, water, and ethanol, is required to produce the polysaccharides. Meanwhile, reinforcing loop R1 shows that recovered waste goes into raw material inflow to potential production, resulting in increased capacity, polysaccharide production, waste generated, and then an increase in recovered waste.

2.2. Model Structure

These adjustments influence material stock, production rate, and further variables along the causality chain. A stock and flow approach is used to quantify these interactions [44]. In this approach, variables that are accumulated over time are represented as stocks, and flows represent the rate of change of stock [45]. In total, there are six main sectors used in the model in Fig. 2. The production sector is where the material flows and is transformed into products and waste. The labor sector adjusts the required workforce based on production efficiency. The production capacity sector is where order, commissioning, operation, and decommissioning occur in relation to available material inflow. The energy consumption sector determines energy flows based on the average energy efficiency level of the current operational capacity and its changes. Financial metrics such as expenses, turnover, and profits are calculated in the finance sector. Lastly, a substrate input sector where system limits affect the raw material inflow.

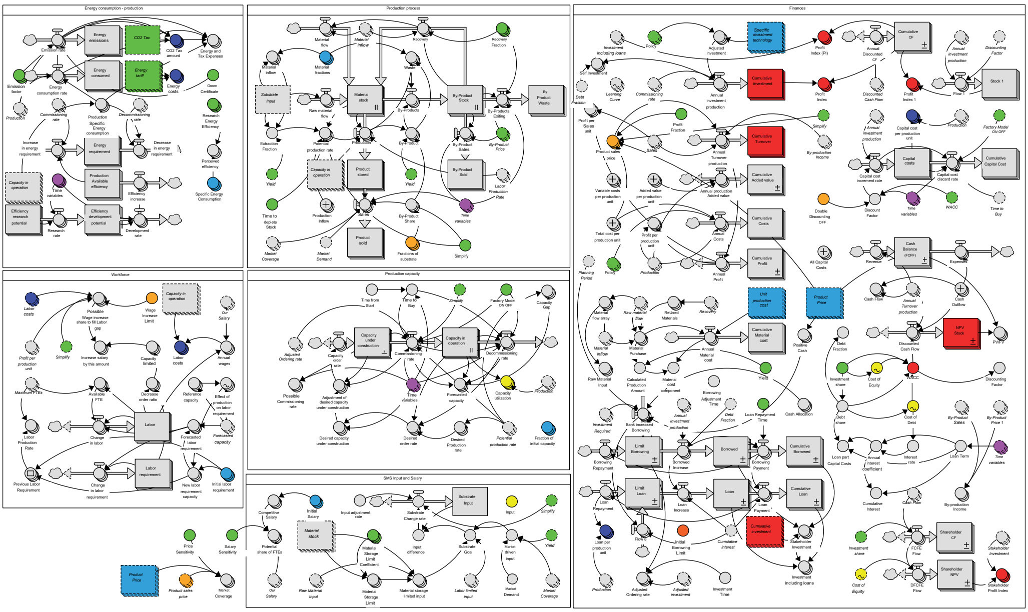

Fig. 2. SD model structure for polysaccharide valorization from SMS.

The number of model variables for each building block is given, and array expansion values are in parentheses: Stocks 49 (94), flows 55 (109), and converters 150 (260). Resulting in 254 (463) total variables. There are 156 (273) equations used in the model.

Implementing an SD model bridges theoretical knowledge with practical application by providing quantifiable relationships between system variables and making complex, cleaner production principles accessible and engaging for students.

2.3. User Interface of the Interactive Learning Tool

To provide easy access to the ILT for students, an educational interface has been developed on top of the SD model in Fig. 2; the ILT is available online on: https://exchange.iseesystems.com/public/testlearntestsagain/cleaner-production/index.html

This interface includes eight pages in total, categorized into five categories. Pages 1–2 include a brief introduction to SMS and its contents. Pages 3–5 show the laboratory setup for polysaccharide extraction, a causal loop diagram of the model in Fig. 1, and a stock and flow diagram for the production process from Fig. 2. As interface users may not be familiar with laboratory setups or SD methodology, the mentioned pages also explain the setup and model. Page 6 shows environmental results in Fig. 3. Page 7 shows socio-economic results. The last page, 8, shows a feedback survey where users can suggest improvements to the interface. Pages 6–7 also show sliders and buttons that can change model input data and assumptions. The users can adjust sliders as they wish between the given minimum and maximum values by pressing the simulate button to see results for the performed simulation. Adjusting these values makes it possible to incentivize or discourage specific actions. For example, assuming other parameters stay the same, an increased water recovery results in decreased raw water inflow. Therefore, this reduces production costs and increases perceived market share, resulting in a more significant turnover than in previous simulations.

Fig. 3. ILE user interface page of model environmental variables and outputs.

2.4. Case Example Presentation in an Interactive Learning Tool

To evaluate the tool and receive information about its use, the following case example was presented to Riga Technical University environmental engineering master's students in the Environmental Technologies course. To familiarize the students with the given tool, they were also presented with the tool's structure, usability, and input data. This presentation took 20 minutes. After the presentation, students could work with the tool – change any parameter and run the simulation to see how the parameters affect the results, which are displayed graphically. This process also took 20 minutes to complete. Students were able to work with both environmental parameters and socio-economic parameters.

2.5. Survey

After running the simulations and exploring the tool, the students also had to give feedback so that the tool authors could evaluate its usability, find out the level of user satisfaction, receive recommendations on the necessary improvements of the tool, and get a general opinion on the use of such tools in the learning process. The survey took 15 minutes to complete.

The survey included 20 questions. These questions were used to assess the effectiveness and user-friendliness of an ILE from multiple standpoints. By asking these questions, the first goal is to identify whether the initial information is proficient, identify gaps that could hinder the user's ability to use the decision-making tool fully, evaluate the ease of understanding, and locate unclear functionalities and potential obstacles. The second goal is to assess the ILT overall, estimate the support of ILT, and receive suggestions for improvement. Questions 1, 3, 5, 7, 9, 11, 13, 14, and 15 are multiple-choice, and the rest are open-ended. Survey questions are provided in Annex 1, Table A1.

3. RESULTS

Over 20 students attended the tool testing lecture, and all participated in discussions about using interactive tools. Only 11 of them provided descriptive feedback. The findings are summarized in the quantitative and qualitative survey analysis below.

After working with the ILT to assess students' responses to multiple-choice questions and relationships between answers and to answer the research question "How do students perceive incorporating ILTs in their curriculum?", a quantitative analysis has been performed. Cronbach's alpha criterion was used for the internal consistency of the scale's items, corresponding to an acceptable level of $\alpha = 0.756$. Question 13 has been removed from this scale as it does not represent information regarding the acceptance of the tool use. Descriptive statistics are given in Table 1. Higher values respond to positive answers. For Q13, the higher value indicates the available simulation end time. For all multiple-choice questions, the median is at the maximum values, means are on the upper boundaries of maximum values, and skewness is negative, meaning that responses are at the positive end of the scale. This trend indicates that most respondents give positive answers. The low standard deviation shows that responses are clustered together. Shapiro-Wilks score shows that the data is not normally distributed. Given the limited number of answers, this behavior is expected. Questions Q1, Q5, Q7, Q11, and Q15 show large negative skewness values relative to the entire set of questions. This indicates that answers to these questions have demonstrated strong positive support for presentation and understanding, and an inclination to see more ILE in the future.

TABLE 1. DESCRIPTIVE STATISTICS OF MULTIPLE-CHOICE QUESTIONS

Question	Median	Mean	Std. Deviation	Skewness (SE = 0.661)	Shapiro-Wilks	Minimum	Maximum
Q1	2	1.818	0.405	–1.923	0.486	1	2
Q3	3	2.455	0.688	–0.932	0.756	1	3
Q5	2	1.818	0.405	–1.923	0.486	1	2
Q7	2	1.909	0.302	–3.317	0.345	1	2
Q9	3	2.636	0.674	–1.8	0.619	1	3
Q11	2	1.818	0.405	–1.923	0.486	1	2
Q13	3	2.182	0.982	–0.429	0.697	1	3
Q14	2	1.636	0.505	–0.661	0.625	1	2
Q15	2	1.818	0.405	–1.923	0.486	1	2

Primarily, descriptive statistics of student questionnaire answers show positive responses to ILE, understanding, reliability, detailedness, ILE overall value, and integration of more ILEs into the curriculum.

Kendall's tau (τ) was calculated for multiple-choice question pairs in Table 2. Significant positive associations have been found among Q1–Q3 ($\tau = 0.606$), Q3–Q5 ($\tau = 0.606$), Q7–Q11 ($\tau = 0.671$), Q3–Q15 ($\tau = 0.606$), and Q5–Q15 ($\tau = 1$). The rest of the pairs did not yield statistically significant correlations ($p > 0.05$). The perfect τ value for Q5–Q15 shows that respondents who understand the buttons, value ranges, and windows in the ILT would like more interactive interfaces presented during lectures. This shows that understanding the presented tool is necessary to be ready to see other similar ILTs. For the Q7–Q11 ($\tau = 0.671$) pair, whether information and results are presented comprehensively in the tool indicates the perceived detail of the tool. Responses in Q7 that said some parts were not comprehensive responded in Q11 that they would like the tool to be more detailed. The Q3–Q15 ($\tau = 0.606$) shows that the tool's understanding is crucial for respondents to have more interactive interfaces presented during future lectures. For the Q3–Q5 ($\tau = 0.606$) pair, the tool's overall understandability is related to the understanding of the buttons, value ranges, sliders, and windows provided in the interface. Finally, the Q1–Q3 ($\tau = 0.606$) pair shows that respondent understanding is also affected by the presenter's ability to explain and provide enough information to partake in the exercise and tool testing.

TABLE 1. KENDALL'S TAU RANK CORRELATION MATRIX

Question		Q1	Q3	Q5	Q7	Q9	Q11	Q13	Q14
Q3	τ	0.606*	—						
Q5	τ	0.389	0.606*	—					
Q7	τ	−0.149	0.271	−0.149	—				
Q9	τ	0.324	0.404	0.324	−0.186	—			
Q11	τ	−0.222	0	−0.222	0.671*	−0.277	—		
Q13	τ	0.081	−0.265	0.081	−0.271	0.336	−0.404	—	
Q14	τ	0.134	0.486	0.134	0.418	0.408	0.134	0.13	—
Q15	τ	0.389	0.606*	1**	−0.149	0.324	−0.222	0.081	0.134

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Students who understand the interface details would like to see more ILEs integrated into their curriculum. This has been shown to be the key answer given the perfect τ value. At the same time, the effective presentation of the ILE and precise design of elements represent whether the students will support ILE integration into the curriculum.

To provide a confidence interval (CI) of possible student proportion support ILT, a Bayesian binomial test was conducted to evaluate support for ILTs in the curriculum (Q15). The test compared whether the proportion of positive responses in Q15 was greater than 0.5, indicating significant support for these tools. Beta (1, 1) was used as a prior distribution due to the lack of previous knowledge about the student support proportion. The 95 % CI shows a large spread [0.553, 0.946] between possible values of the proportion of students that support ILT integration into the curriculum. The BF_{+0} value of 6.086 indicates moderate evidence for the hypothesis. Interval ranges show that it is very likely above 55.3 % and could be as high as 94.6 % of the students show support for ILE integration into the curriculum. However, there is uncertainty about the exact proportion.

3.1. Qualitative Survey Analysis

A qualitative analysis was performed on the open-ended questions to assess students' improvement points and comments. The questions are Q2, Q4, Q6, Q8, Q10, Q12, Q16, Q17, Q18, Q19, and Q20.

Most students left Q2 blank, and one respondent noted that “more explaining would be needed.” It could be possible that the tool was too complex for the student or some variables were not clearly explained. One student reported that everything was well presented.

For Q4, most students did not indicate any issues, meaning the ILE is generally understandable after brief familiarization. One student highlighted the problem regarding the sequencing of pages as it is possible to navigate both by buttons in the lower corners and the navigation pane in the top-right corner. Two students reported that more practical usage and background knowledge could significantly improve their understanding of ILE.

Regarding Q6, one student suggested renaming a variable from “variable switch” to “additional variables” for clarity. The rest of the students left this question blank.

Most students reported in Q8 that the presented tool is comprehensive, besides one student who reported, “I can’t answer.”

Regarding ILE reliability in Q10, one student reported “as reliable as simulation can be,” suggesting a realistic acceptance of simulation constraints. Another student would like to “watch it again,” suggesting a repeated presentation of the ILE case study. One of the students suggested built-in scenarios, such as energy savings, which would improve credibility and understanding of simulation outcomes.

In Q12, two students noted that “many details are included” and “there is much detail, many variables,” which make the ILE seem overwhelming.

Some students reported in Q16 that “small training” and “no specific knowledge is required, but maybe a little time and preparation” would help them use the ILE. One student reported that “graph understanding” is necessary to understand the outputs the ILE provides. Another student noted that it is needed “to understand process and impact,” showing a must-have background knowledge of the ILE.

The learning curve is the primary concern when using ILE in Q17. Students report that first-time use requires significant time to dwell on the tool’s mechanisms. Some have identified that the main barrier is knowledge of mushroom substrate and its applications. One student expressed that the presentation of ILE while using ILE on their laptops has distracted them from the presenter.

Students provided a wide range of information regarding the time required to understand the tool's functionality in Q18. Reports range from "15–20 minutes", "about 60 min", "~ two hours", "5 hours," and an entire working day. This wide range may be represented by background differences between student levels of understanding as some find ILE easy to grasp, while others require more time and practical use of the tool.

Suggestions for ILE improvement include "reducing or dividing the variables into sections" as currently they are clustered together by commonality, but this is not stated anywhere in the ILE, and "preparatory description" saying that a user manual would be beneficial.

Students have expressed support in Q20, where any previously unmentioned information could be stated. Most compliments, such as "Thank you!" and "I'm shocked, very well done, amazing work," suggest a strong positive reception of the ILE.

Reflection on qualitative analysis shows that there is a constant narrative. While the ILE looks professionally designed and detailed, it is simultaneously complex and requires more guidance for intuitive navigation. Students mentioned a need for introductory training and a user manual for the ILE. Overall, the students are very supportive of the presented ILE.

4. DISCUSSION AND CONCLUSIONS

An interactive ILE using SD software Stella Architect has been developed to facilitate understanding and analysis of SMS and its socio-economic and environmental effects of the polysaccharide extraction method. Initial sections introduce SMS, followed by informative presentations of the laboratory setup, causal loop diagram, a partial SD model structure, and production process with complete explanatory notes for user accessibility. The presentation and testing of an interactive ILE for master's students in Environmental Technologies at Riga Technical University resulted in positive feedback and valuable insights. The tool was appreciated for its understandability, detailed information, and helpful support in decision-making and learning. Most students highlighted the importance of interactivity in educational tools, a desire for more such interfaces in lectures, and available interactivity that improves comprehension and engagement. However, they have found the ILT to be complex and would like to have a user manual and more time of working with the ILT.

Survey responses indicate positive perception regarding the ILE integration into different curriculums underlines its effectiveness in enhancing understanding and engagement in a cleaner production context, contributing to quality education. It also stands out in analytical depth and user engagement capabilities. Feedback from the interface tests will guide the tool's authors in improving its usability and integrating similar interactive resources into other educational contexts, including student involvement in its evaluation to ensure its effectiveness and applicability in academic settings.

In summary, the use of ILT in the Environmental Engineering cleaner production course is supported by the students. This approach lets students interact with the challenges faced in the course through a simulated environment.

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ANNEX

TABLE A1. THE QUESTIONNAIRE WITH ANSWERS

Questions	Answers			
1. Were you given enough information about the tool to use it and take part in the exercise?	Yes	Partially	No	
2. What information was missing?	Open-ended answer			
3. How would you rate the tool's understandability?	Understood everything	Partially	Did not understand	
4. Which parts of the tool caused the confusion and were not understandable?	Open-ended answer			
5. Did you understand the buttons, the value range of the slider and the windows of the tool?	Yes	Partly	No	
6. What was incomprehensible about the functionality of the tool? Which buttons, slider values or windows you did not understand? What would you like to change?	Open-ended answer			
7. Was the information and results presented comprehensively in the tool?	Yes	Partially	No	
8. What information and results presented in the tool was not comprehensive?	Open-ended answer			
9. Do the simulation results provided by the tool seem reliable to you?	Yes	Partly	No	
10. Which parts of the simulation results did not seem reliable to you in the tool and why?	Open-ended answer			
11. How would you rate the level of detail of the results provided by this tool?	Detailed	Partially detailed	I prefer more consolidated results	
12. What details were missing but you would like to see in the model?	Open-ended answer			
13. What simulation period would you like to see for the model?	Until 2030	Until 2040	Until 2050	
14. In general, how do you rate this platform as a source of information and a tool to support decision-making?	Very valuable	Valuable	Low value	Not valuable
15. Would you like to have more interactive interfaces presented during lectures?	Yes	No	Maybe	
16. In your opinion, is there any specific knowledge required to use this tool? If so, which ones?	Open-ended answer			
17. In your opinion, what could be the main obstacles to using this tool for daily work/study?	Open-ended answer			
18. How much time do you estimate an end user will need to understand the tool's functionality and use it to perform certain simulations in order to obtain valuable results?	Open-ended answer			
19. Do you have any specific suggestions on how this tool could be improved?	Open-ended answer			
20. Is there any other information or opinion that we have not asked for but that you would like to express?	Open-ended answer			