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Enhancing Curriculum Through a Required Vertically Integrated Project (RVIP)

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Enhancing Curriculum Through a Required Vertically Integrated Project

Abstract

This paper presents the design, implementation, and preliminary evaluation of a Required Vertically Integrated Project (RVIP) on luminescent solar concentrators (LSCs) within an undergraduate mechanical engineering curriculum. Unlike traditional vertically integrated projects (VIPs), which are typically optional, this model embeds project-based learning across required courses, ensuring broad participation and long-term curricular sustainability. The RVIP connects Materials Science, Numerical Methods, and Heat Transfer through assignments connecting on optical and thermal subsystems of an LSC.

Results from student surveys and performance-based assessments indicate strong engagement and evidence of systems-level reasoning. Across courses, the majority of students successfully completed technical tasks and demonstrated the ability to connect physical mechanisms, modeling assumptions, and design trade-offs. Students also showed increased awareness of interdisciplinary dependencies, particularly between optical efficiency and thermal management. This cross-course integration was implemented with minimal disruption to existing course structures and faculty workloads.

This work demonstrates that a required, multi-course project can achieve many of the educational benefits associated with traditional VIPs, such as sustained engagement and systems thinking, while remaining scalable within existing course structures.

Introduction

The multi-disciplinary system-level project presented in this paper is implemented as a Required Vertically Integrated Project (RVIP) within the undergraduate mechanical engineering curriculum at Rensselaer Polytechnic Institute a private, research-intensive, engineering-focused university in the United States. Rather than serving as an optional or extracurricular experience, the RVIP embeds sustained, design and project-based learning experiences directly into required courses, ensuring broad student participation and long-term curricular sustainability. This RVIP initiative is part of a broader institutional effort supported by the National Science Foundation's IUSE/Professional Formation of Engineers: Revolutionizing Engineering Departments (IUSE/PFE: RED) program, which seeks to enhance student learning, professional formation, and engagement within engineering education.

Prior work in engineering education has demonstrated the value of vertically integrated projects (VIPs) in promoting increased student engagement and persistence as well as improved career readiness and employment outcomes [1]. However, because these projects are typically offered as electives and/or extracurricular activities, participation is limited and disproportionately favors students who have greater available time, have more knowledge of how to navigate higher education, and have a higher level of confidence in their abilities. Moreover, such programs require substantial additional institutional resources, including faculty effort, dedicated laboratory space, and administrative support.

Numerous studies on project-based learning in courses have reported gains in students' content knowledge, learning strategies, skills, and motivation [2], though such efforts are often confined to single courses and lack longitudinal coherence. While some of these benefits overlap with those of VIPs, a VIP is distinguished by its association with improved employment outcomes. One study reported that students who participated in VIP for three or more semesters had substantially higher odds of having secured employment prior to graduation [1]. The magnitude of this association is second only to that of co-op participation and exceeds that associated with internships, suggesting that extended VIP participation provides a competitive edge in the labor market, which is equal to, and in some cases stronger than, more traditional forms of work-integrated learning. In contrast, variables such as GPA and participation in Greek life show markedly weaker associations with job placement. These findings suggest that sustained, multi-semester engagement in authentic project work, rather than short-term experiences or general academic performance, are most strongly associated with early employment outcomes.

Additional literature beyond that focused on VIPs, specifically, emphasizes the importance of connecting concepts across courses and years to help students build progressively richer mental models of engineering systems. For instance, Xu argues that when traditional disciplinary silos are broken through interdisciplinary curriculum models, students benefit in multiple ways [3]. First, interdisciplinary integration encourages students to synthesize knowledge from multiple fields, enabling them to develop more holistic and flexible understanding of complex, real-world problems that cannot be solved with the content of a single course or even a single engineering domain. Second, it fosters deeper conceptual coherence beyond what siloed courses typically offer, as students must relate, integrate, and apply diverse concepts, methods, and analytical frameworks to a shared challenge rather than in isolation. Third, it enhances students' *systems-thinking skills*, as they work with peers and instructors from different disciplinary backgrounds and negotiate multiple perspectives toward a unified solution. Systems thinking skills are notoriously difficult to develop in traditional academic environments due to the limited opportunities for authentic, integrative practice in conventional engineering curricula, yet they are increasingly indispensable for engineers working in complex, interdisciplinary, and rapidly evolving professional contexts [4-7].

Building on these findings, the RVIP model presented here is intentionally designed to provide all students with the sustained, multi-semester engagement that has been shown to be associated with improved employment outcomes and promote systems-level thinking. The RVIP consists of vertically integrated, interconnected, course-based design challenges or projects embedded within required courses from the freshman through senior years, ensuring that every student participates in authentic engineering work for multiple semesters as part of the core curriculum. By distributing responsibility for the project across coordinated courses, this approach aims to achieve the longitudinal continuity characteristic of successful multi-semester VIPs without requiring dedicated faculty positions or increased faculty workload beyond the initial implementation. Moreover, unlike research-centered VIP models where most students often focus on a singular aspect of a larger problem, the RVIP aims to engage students in multiple, interdependent aspects of system design, analysis, and implementation across courses, deliberately reinforcing cross-course conceptual connections. In this way, the RVIP model presented here aims to both replicate the career-readiness benefits of extended VIP participation at scale and to address the well-documented difficulty of cultivating systems thinking within traditionally siloed engineering curricula.

In addition to describing the structure of the RVIP, this paper also presents measurable student outcomes, including task completion rates, evidence of conceptual understanding, and the ability to reason about interdisciplinary trade-offs. Large language models (LLMs) were employed as a supporting tool to analyze open-ended responses, with all results subsequently audited by one of the authors.

The remainder of this paper first describes the technical theme selected for this RVIP pilot and the rationale for its integration into required courses. It then presents the three curricular segments that have been developed and deployed, along with preliminary results on student outcomes. Finally, the paper concludes with a discussion of the main takeaways from this pilot effort.

Technical Theme

To pilot our RVIP, we selected a project centered on luminescent solar concentrators (LSCs). LSCs consist of a transparent polymer sheet embedded with luminescent species and coupled to photovoltaic (PV) cells mounted along some or all its edges (Fig. 1 a). Incident sunlight is absorbed by luminescent species (such as organic dyes, quantum dots, or phosphor particles) and re-emitted at longer wavelengths. A significant fraction of this emitted light undergoes total internal reflection within the sheet and is guided toward the edges, where it is concentrated onto the PV cells, thus enhancing their power output. The luminescent species serve a dual role: they increase the probability that light propagates laterally within the sheet rather than escaping perpendicularly, and they introduce a wavelength shift in the light concentrated onto the PV cells. The wavelength shift facilitates a more efficient conversion of sunlight. The largest portion of AM 1.5 solar spectrum falls outside the spectral response of a crystalline silicon solar cell [8]. Thus, incident sunlight lies at wavelengths that are inefficiently converted to electricity, which motivates the use of luminescent species to absorb shorter-wavelength light and re-emit it at longer wavelengths where the silicon solar cell response is higher.

The potential for solar energy conversion of LSC was recognized in the 1970s, when they were first explored during the energy crisis, due to their low fabrication cost relative to traditional solar cells. However, practical use only emerged more recently. They were first commercialized by *Soliculture*, a California company, beginning around 2012 as semitransparent greenhouse materials [9]. They are also being piloted in the Netherlands as highway sound barriers [10]. Because LSCs can be fabricated in a wide range of forms, colors, and sizes using conventional building materials, more recently they have been explored as building-integrated photovoltaics

(BIPV) [11], multifunctional building envelope components that harvest solar energy while simultaneously protecting the structure from environmental exposure.

We selected this platform because it offers a rich, visually compelling, and authentic context for multidisciplinary learning, spanning materials, numerical modeling, optics, heat transfer, fluids, mechanics and system integration. In the pilot phase of this study, we integrated three distinct assignments into three separate engineering courses. These included Materials Science (first-year foundational course), Numerical Methods and Programming for Engineers (second-year

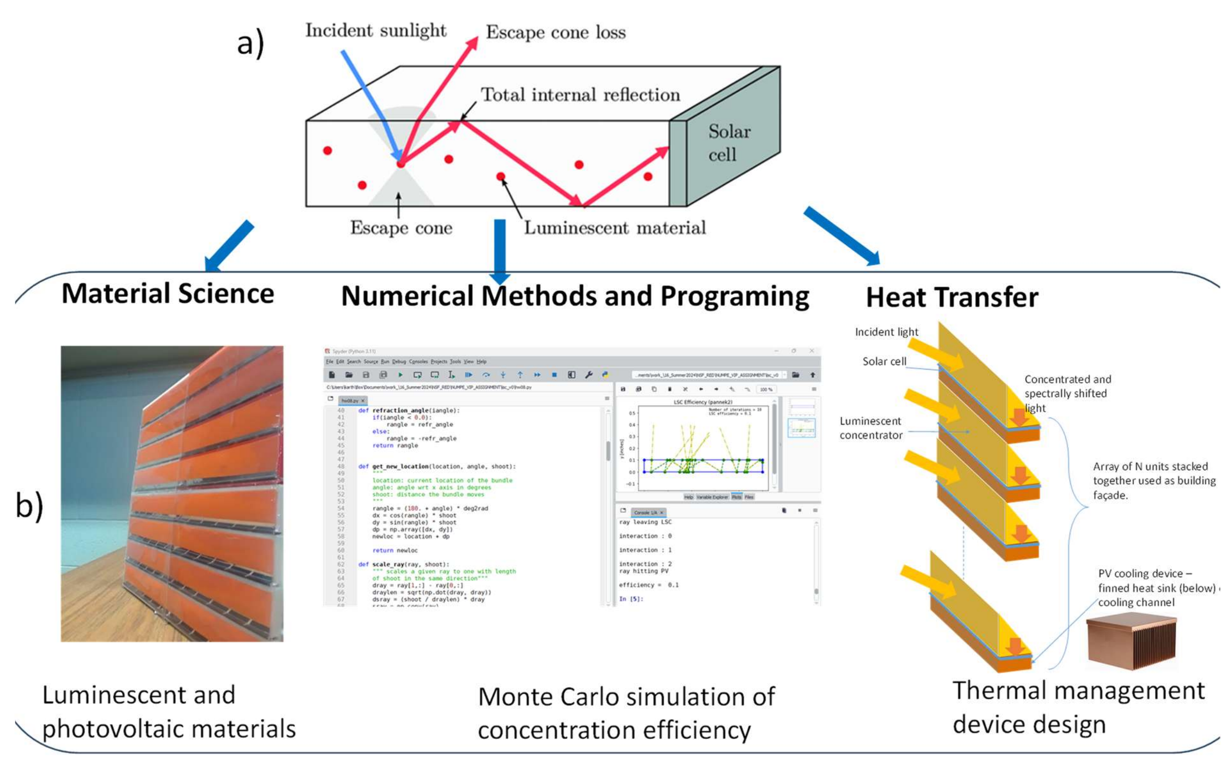

Figure 1. a) Operating principle of luminescent solar concentrators. b) Current assignment implementation.

major-specific course), and Heat Transfer (third-year major-specific course), as illustrated in Fig. 1b. A planned extension of this work is to expand the RVIP project to a junior level mechanics course, an aspect that is not discussed in this paper.

Course Implementation of Associated Content and/or Assignments

Materials Science Segment

In the Materials Science course, required for all engineering students, we incorporated the LSC as an example of contemporary photovoltaic applications during the unit on semiconductor devices Spring 2025. As part of the lecture-based component of the activity, students were introduced to the fundamental optical properties of quantum dots, particularly their absorption and emission spectra and their technological significance in LSC systems. As discussed in the previous section, within LSC architectures, quantum dots function as photonic conversion elements, absorbing high-energy, short-wavelength incident sunlight and subsequently re-emitting it at longer wavelengths that align more closely with the optimal spectral response range of photovoltaic devices. This spectral shifting phenomenon enhances spectral matching and thereby improves overall energy-conversion efficiency. A complementary design-oriented in-class activity was developed to reinforce these concepts, asking students to pair quantum dots with photovoltaic cells exhibiting different spectral responses. However, this activity was not implemented during the initial rollout due to logistical challenges. Instead, in the initial implementation of this segment, students were asked to respond to an open-ended question in the form of an exit ticket at the end of class: "*What factors account for the incomplete conversion of the sun's energy to electrical current?*"

All student responses to the open-ended exit-ticket question and all survey responses reported in this paper were analyzed using a qualitative approach assisted by large language models (LLMs), specifically Microsoft Copilot cross-checked against a secondary LLM (ChatGPT). Prior to analysis, all responses were compiled and stripped of any identifying information. Both LLMs were then prompted to identify, categorize, and quantify recurring themes across the dataset. Each student was counted once per category if any of their responses referenced that concept, regardless of repetition, to avoid overrepresentation of individual respondents.

For this analysis, one of the co-authors interacted with the LLMs using prompts such as "Quantify how many students responded heat loss/conversion of energy to heat." and "Quantify what is the next most common factor identified." For the second prompt, both models produced a ranking of the three most common factors. Copilot initially produced an inaccurate count for the second most common factor. However, when prompted to list all responses associated with that category, its output converged with that of the ChatGPT model.

The results indicate that a majority of students frame photovoltaic inefficiency primarily in terms of energy dissipation as heat, with 17 of 31 students (approximately 55%) explicitly identifying thermal losses or heat generation as a limiting factor. This suggests that students readily recognize heat loss as a dominant constraint in energy conversion processes. A substantial fraction of the class, 12 students (approximately 39%), also identified band gap or sub-bandgap absorption limits, suggesting an emerging understanding that not all incident photons can be absorbed and converted due to the discrete electronic structure of the semiconductor. Finally, 10 students (approximately 32%) pointed to reflection or optical losses, suggesting awareness that a portion of the incident light is lost before it can even participate in the conversion process. These results indicate that introducing this emerging-technology content supported conceptual awareness of efficiency limitations and design strategies in solar-energy systems.

Numerical Methods and Programming for Engineers Segment

To build on the conceptual foundation discussed in previous section, the project was subsequently extended into a required sophomore-level mechanical engineering course, where students engaged in a more applied and quantitative exploration of LSC behavior as part of a comprehensive computational homework assignment. In this course, students performed Monte Carlo ray-tracing simulations to evaluate how LSC geometry affects light-concentration efficiency, applying the optical principles discussed in Technical Theme section. As part of this individual assignment, students modeled a simplified two-dimensional LSC system shown in Fig. 1a and simulated the trajectories of incident light bundles, accounting for transmission, reflection, refraction, scattering, and absorption events until photons either reached the photovoltaic surface or were lost. By varying incident angles and starting positions and computing the resulting efficiency as the fraction of rays absorbed by the PV interface, students were able to directly connect physical light-interaction phenomena to device-level performance measures. This assignment was first implemented in the Fall semester of 2024.

A survey was distributed to the students as part of the homework assignment. There were 138 total submissions. The survey included the following open-ended questions.

1) Were you able to generate a correct plot?
2) In your own words, describe what information you think the simulation (based on what you see in the plots) provides to you. (If you do not have your own plots, use those in the assignment PDF.)
3) Choose any one geometric variable in this analysis (e.g., length, height, solar angle, etc.) to change and write your prediction for how varying it will affect the efficiency and why you think so. Then test your hypothesis by running the simulation with your perturbed value and describe the effect on the results that you observe.
4) From your own experience, how might coursework in Chemistry or Materials Science add knowledge to make this simulation more accurate?
5) Is there anything else you want us to know about your work on this homework project (good or bad)?

For four of the survey questions (1, 2, 4 and 5) the two LLM were employed to assist the quantitative analysis. The prompts for analyzing the four questions were:

a) "In the attached file, count the number of "No" responses, responses equivalent to "No", as well as blank entries to the question: "Were you able to generate a correct plot?""
b) "How many responses do not mention any of the following ray-interaction concepts (or their close synonyms): reflection, transmission, refraction, absorption, concentration, or efficiency, and instead contain only vague or generic descriptions (e.g., statements such as "it shows …" without explaining the physics)?"
c) "Count responses that are blank or that fail to connect the Monte Carlo simulation homework problem on luminescent solar concentrators to coursework in chemistry or materials science."
d) "Count the number of students who did not provide a reflective answer, that is, responses that were blank or consisted only of 'no' or 'nope."

For survey question 3, all responses were reviewed manually by a single co-author to ensure that all relevant features of the student submissions were captured.

In response to prompt (a), ChatGPT identified 3 negative ("No") responses, while Copilot initially identified 12, with 3 overlapping between the two models. All Copilot-flagged responses were manually reviewed. Several were excluded because, although phrases such as "not working" appeared, the students ultimately reported successful completion. After manual verification, only 7 responses were truly negative. Both ChatGPT and Copilot failed to detect one blank entry, which was identified and counted manually. Thus, a total of 130 out of 138 students (94.2%) reported successfully generating a correct plot.

Additional analysis using both LLMs was conducted to identify the most commonly reported challenges. The two models did not fully agree on the ranking or categorization of these difficulties. ChatGPT identified the three most frequent challenges (in order) as: (i) using plotting libraries and functions, (ii) understanding and debugging the code, and (iii) fixing syntax or general coding errors. Copilot, in contrast, reported the most common challenges as: (i) general debugging issues (e.g., tracking down logic errors or mismatched array operations), (ii) difficulties with vector geometry (including perpendicular vectors, rotations, and handling radians), and (iii) implementing the glass-interaction logic correctly, particularly distinguishing transmission from reflection using critical-angle conditions.

For survey question 2 (prompt b), the two LLM models produced very different initial counts: Copilot flagged 8 responses, while ChatGPT flagged 41. Only one response identified by Copilot did not appear in ChatGPT's larger flagged set. All responses flagged by either model were manually reviewed for accuracy. After verification, only 10 responses were determined to indicate poor or no understanding of the physical meaning of the simulation or a misinterpretation of the question in the homework assignment (e.g., "The information that the simulation provides to me is that photovoltaic cells are extremely inefficient and most of the solar rays that enter the cell escape," or "I believe it gives a good simulation of light bouncing around in a fluid. Since there is an element of randomness, I think the iterations are especially important for researching and developing systems such as solar panels."). Of these 10 responses, 2 overlapped with Copilot's flagged set. Thus, 130 out of 138 students (94.2%) were ultimately judged to have demonstrated full or partial understanding of the simulated physics.

As a side note, many of the responses flagged by the LLM models actually demonstrated fairly good understanding of the underlying physics. In several cases, the students even used many of the predefined keywords, though not always with perfect technical accuracy. For example, one student wrote: *"The simulation gives us a detailed look at how light interacts with different surfaces—whether it gets reflected, transmitted, or scattered. Looking at the plots, we can see how the light spreads after it hits the surface, which tells us about how efficiently the system is capturing or transmitting light. For example, in a solar collector setup, we might see more rays reflected back into the system, which is good for concentrating light. On the other hand, if the goal is to let light pass through the system, we'd expect to see more rays transmitted. The simulation also shows how scattering affects this behavior, which is useful when optimizing the system for better performance."* This illustrates that current LLM-based analysis cannot reliably distinguish between superficial wording and genuine conceptual understanding.

In response to survey question 3 (manual counting), 109 of 138 students (78.98%) both stated and tested a prediction about how a change in LSC geometry (height or length) or angle of incidence would affect the concentration. These students typically described their results in terms of performance or optimization, for example, "changing the angle increases how many rays hit the cell" or "increasing the length improves capture but also increases losses." The remaining 29 students either did not submit a response (blank entry) or stated a hypothesis without carrying out a test, in some cases noting that their code did not work.

For question 4 (prompt c), the two LLMs produced partially overlapping sets of flagged responses. ChatGPT identified 9 responses as not connecting to relevant coursework, while CI-Pilot flagged 48 responses, 8 of which overlapped with ChatGPT's set. After one co-author reviewed manually all flagged responses, it was found that 128 of 138 students (≈92.75%) made statements referencing concepts commonly covered in chemistry, materials science, or physics that would improve the realism of the Monte Carlo LSC simulation. The most frequently cited ideas involved refractive index, absorption, emission, and material-dependent optical behavior. Students expressed these concepts with varying levels of precision, for example, from statements such as "chemistry would let us model how light bends and is absorbed in different materials instead of assuming ideal behavior" to more detailed explanations like "Chemistry or Materials Science coursework could provide insights into the optical properties of materials, such as refractive indices, absorption coefficients, and scattering behavior, enabling more accurate modeling of light interactions and energy-loss mechanisms within the LSC."

Finally, for question 5 (prompt d), 132 of 138 students (≈95.65%) provided reflective comments, frequently noting that the project was *"challenging but helpful," "made the physics* *more visual,"* or *"helped connect coding, geometry, and optics."* For this query, both LLM models returned the same count and identified the same set of responses.

Overall, the survey data suggests that most students were not only able to run the simulation successfully, but also used it to reason about physical mechanisms, geometric design choices, and modeling assumptions in an integrated, system-level manner. Many students explicitly connected geometric configuration and ray-incidence angles to efficiency outcomes, while also recognizing that incorporating more realistic material properties, such as refractive index or absorption, would further influence those results. These responses indicate that students were reasoning across interacting components of the model rather than treating individual elements in isolation.

Heat Transfer Segment

The final segment of the RVIP sequence was implemented in a required Heat Transfer course for mechanical engineers. In this course, typically taken at the junior level, students shifted their focus from optical efficiency to the thermal management of LSCs, exploring how effective heat dissipation strategies are required to maintain photovoltaic (PV) operating temperatures within an optimal range. This emphasis reflects a critical aspect of solar energy system performance, as elevated operating temperatures significantly reduce PV efficiency and negatively impact long-term reliability and device lifespan. Once again, the overarching pedagogical objective of this segment was to encourage students to think beyond component-level analysis toward system-level reasoning involving coupled thermal, optical, and, eventually, fluid mechanics design considerations.

To implement this learning objective, a semester-long RVIP design project was developed and first offered in Spring 2025. The project required students to design a finned heat sink (Fig. 1b, far right) for an LSC system with a light concentration factor (i.e., light flux on the PV) of 1.2. The design focused on a wedge-shaped LSC with prescribed geometric parameters operating under worst-case solar loading conditions, and students were required to ensure adequate heat dissipation for a 1 cm × 1 m PV strip using the heat sink as the sole cooling mechanism to maintain the PV temperature at 35 °C or below. Student deliverables included CAD drawings, a fully programmed Excel spreadsheet, and a technical report and teams consisted of two students only.

As in the previous segment, a survey associated with the project was deployed and counted as an extra-credit assignment. The survey focused primarily on conceptual understanding, perceived difficulty, and evidence of systems thinking. It included the following questions:

1) Was this assignment more or less difficult than what you were expecting?
2) Please indicate if you have taken any of the following classes (check all that apply): Numerical Programing (Fall 24), Numerical Methods and Programing (Spring 25), Materials Science (Spring 25).
3) How would you describe the role of heat transfer in the design of solar cells?
4) If you've taken Numerical Programming and worked on the Monte Carlo homework, how does optimizing radiation concentration affect the performance of a luminescent solar concentrator, and what trade-offs or challenges arise as a result?
5) Can you give an example of a system where optimizing one part creates new challenges in another?

A total of 136 student responses were collected. As in the previous analysis, the two LLMs were used to assist with the quantitative analysis of responses to all questions. The interaction with the models was structured using the following prompts, corresponding to the survey questions above:

a) "Count the number of 'More' responses."

b) “Count the number of responses from students who have taken Numerical Programming Fall 2024, Numerical Programming Spring 2025, and Materials Science Spring 2025.

c) “Count responses that do not link heat transfer to solar cell efficiency or system performance.”

d) “Identify the most common response to the question: how does optimizing radiation concentration affect the performance of a luminescent solar concentrator, and what trade-offs or challenges arise as a result?”

For Question 1, 43.38% of students reported that the assignment was more difficult than expected. Both LLMs reported the same count (59 students). For Question 2, 55 students reported having taken Numerical Programming in Fall 2024, 17 in Spring 2025, and 11 students reported having taken Materials Science.

For Question 3 (LLM query c), ChatGPT flagged 46 responses, while Copilot flagged 54 responses as not linking heat transfer to system performance. Some flagged responses were identical, but many did not overlap between the two datasets. Both flagged sets were reviewed manually by a co-author, and a total of 6 responses were ultimately judged as not fully or even partially linking heat transfer to system performance. Some of these six responses appear to reflect misunderstandings of the question (e.g., “Solar cells absorb energy from the sun and lead to heat generation through conduction, convection, and radiation,” or a response describing only team responsibilities), or were extremely vague (e.g., “Essential”). Interestingly, as also observed in the Numerical Programming LLM data processing, some responses flagged by one or both models clearly did indicate a meaningful link between heat transfer and system performance (e.g., “Heat transfer is important for allowing solar cells to operate at their optimal temperature while receiving a heat flux that cannot be converted to energy.”).

In response to query (d) (corresponding to Question 4), both LLMs produced almost identical summaries. The most common response was that optimizing radiation concentration improves the performance of an LSC by increasing light capture and guiding more photons to the edges (thus increasing electrical output/efficiency), but introduces trade-offs such as increased reabsorption losses, optical losses, thermal buildup (heating), and potential material degradation. Both models reported approximately the same number of responses with meaningful reflections (87 for ChatGPT and 86 for Copilot). The remaining students either did not respond or indicated that they had not taken the Numerical Programming course with the relevant assignment, although in one case a student still correctly identified the expected trade-off between light concentration and overheating.

Lastly, for Question 5, the response analysis was done fully manually. Only four students did not provide a response. The remaining students discussed trade-offs across a wide range of systems, from consumer products to semiconductor manufacturing to thermal systems (e.g., “In a cooling tower, increasing water flow rate improves evaporative cooling, but increases pumping power requirements and operating costs.”).

Cross-cutting Themes

Across the three participating courses, while student engagement and instructional impact varied, they collectively demonstrate the promise and practical constraints of the multi-course RVIP implementation. In Materials Science for Engineers class, while the instructor observed positive student engagement during the module, the short 30-minute time allocation significantly limited opportunities for in-depth conceptual development, design work, or explicit connection to subsequent RVIP components. These observations, along with logistical challenges associated with cross-department coordination further constrained sustainability, making continuation of this specific intervention unlikely. In contrast, the Numerical Methods and Programming for Engineers assignment was widely viewed as a valuable and authentic application of programming and numerical methods, with students describing it as intellectually engaging and appropriately challenging relative to other coursework. Consequently, this component will be continued, with planned refinements to diversify deliverables and input parameters to strengthen learning outcomes. Similarly, in the Heat Transfer course, students valued the real-world relevance and integrative nature of the project. Successful implementation of this multi-course initiative required substantial cross-disciplinary faculty collaboration, and most participating faculty were highly supportive when provided with clear instructional materials and structured guidance. As these materials mature, instructors are also building capacity and understanding of how to assess student learning and RVIP impact.

Conclusions

This paper presented the design, implementation, and initial assessment of an RVIP centered on LSCs within a mechanical engineering curriculum. Unlike traditional VIP models, which are typically elective and reach only a subset of self-selected students, the RVIP framework embeds a multi-semester, design and/or project-based experience directly into required courses that encourage system-level thinking.

Results from the three pilot implementations demonstrate that this approach is both feasible and instructionally valuable. From an implementation perspective, this work suggests that RVIP-style integration may replicate many of the pedagogical benefits of multi-semester VIP participation at scale, without requiring additional credit hours, extracurricular commitments, or dedicated program staff and infrastructure. The substantial amount of work on developing and refining activities with collaboration across multiple courses and faculty, while somewhat beyond standard expectations for many faculty, is an essential element of transforming undergraduate instruction to support students' real-world problem-solving and knowledge integration. Future work will focus on extending the project into the planned mechanics course, refining assessment instruments to better measure longitudinal development of systems thinking and tracking longer-term impacts on student learning and professional outcomes.

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Conflict of Interest Disclosure

D.-A. Borca-Tasciuc is a co-founder of Troy Solar Corporation, which specializes in developing building-integrated technologies incorporating luminescent solar concentrators. This relationship is disclosed in the interest of transparency and did not influence the study design, data collection, analysis, or conclusions of this work.

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