Understanding How Learners Grapple with Wicked Problems in Environmental Science

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Abstract: Environmental science standards are calling for a perspective that highlights how social and natural systems interact. In order to properly deal with the “wicked problems” arising from this interaction, learners must recognize that there is “no right answer”, since solutions require compromise. They must also use spatial concepts instrumentally to reason about these systems. We propose to address these challenges by adapting authentic complex human-natural systems models into collaborative learning experiences. To do so, we need to better understand the challenges learners face as they use simulations to link spatial reasoning with dynamic processes. This paper presents two cases where we examine learners’ spatial and problem-solving strategies as they interact with a modified stormwater management model. We show that learners require support for core spatial reasoning skills and for problem solving around wicked problems. We then recommend forms of scaffolding and further development.

Introduction

Over the past decade there has been increased acknowledgement that “mile wide, inch deep” coverage of largely factual content is insufficient to prepare future scientists and scientifically literate citizens (NAE, 2008), causing the College Board to embark on the redesign of four AP (Advanced Placement) science courses (Biology, Chemistry, Environmental Science, and Physics) in June 2006. The changes made to the AP Environmental Science standards have placed increased recognition on the importance of taking a complex systems perspective on scientific phenomena such as ecosystems (College Board, 2009). Agent-Based Models (ABMs), one approach to complex systems modeling, can facilitate multidisciplinary learning about the science and policy issues arising from human-environment interactions, but research is needed on how to make these models intellectually and pragmatically accessible to learners. This project addresses that need by developing and testing new tools and pedagogical strategies using an iterative design-based research approach. Our first exploration of these issues engages learners in Green Infrastructure (GI) planning, an authentic problem-based context incorporating Urban Planning (UP) and Environmental Science (ES) disciplines. GI is defined as "an interconnected network of green spaces that conserves natural ecosystem values and functions and provides associated benefits to human populations" (Schilling & Logan, 2008). GI often takes the form of vegetated swales or green roofs that aim to minimize urban stormwater runoff and associated pollution. Since communities do not have infinite resources, they must make strategic decisions about where GI elements will make the most impact.

In our collaboration with disciplinary experts from both UP and ES, we have identified certain key reasoning skills required to grapple with challenges at the intersection of human and natural systems. While others have investigated challenges of learning about complex systems (Hmelo-Silver, Marathe, & Liu, 2007), two things set our learning challenges apart. First, the complex systems present in UP and ES are fundamentally defined by their spatial properties and relations. Second, in order to understand how human (UP) and natural (ES) systems interrelate, one must study how their spatial properties and relations intersect. Similarly, the integration of policy or economics transforms these complex problem spaces into “wicked problems”, a class of ill-structured problems originally defined in UP literature (described further below). This exploratory study focused on a subset of spatial reasoning skills, and on one critical skill for grappling with wicked problems: learning to compromise across multiple competing demands.

The ABM we used in this study was adapted from a GI planning ABM, *L-GrID*, developed for the Illinois Environmental Protection Agency by the project’s disciplinary expert co-PIs (Zellner et al., *in progress*). We recruited pairs of undergraduates (to act as proxies for high school seniors who might be in AP Environmental Science courses), and asked them to engage in an authentic GI problem-solving task with the ABM. Because this was a lab-based study, to encourage them to take the problem solving task seriously, we borrowed from methods used in experimental economics. The ABM was structured to contain two competing reward functions, and participants received a bonus cash payout proportional to their optimization of these two functions. We wanted to observe how the participants strategized as they tried to optimize, to better understand how we can support the reasoning skills we identified as being key to the domain. This paper describes how we derived those key skills, then illustrates via case studies how participants used these skills to address a wicked problem, and concludes with recommendations for further development of both ABM tools and the supporting curriculum for multidisciplinary UP and ES learning.

Background

Content Domain: The Intersection of Environmental Science and Urban Planning

To introduce students to the fields of ES and UP, we chose to work with a complex systems model that represents rare stormwater events. This model incorporates elevation, land usage, roads, and sewers, and demonstrates how the placement of green infrastructure (in the form of rain gardens) affects stormwater movement. Our study allowed students to place these gardens on a map of 20 city blocks with various land uses (residential, business, and industrial) that can support differing numbers of rain gardens. The simulation shows the effects of a "hundred year storm" on the area, illustrating how the arrangement of gardens leads to more or less effective stormwater management. Effectiveness is defined by the two competing reward functions: one stresses a social priority (cost), and the other stresses a natural priority (time for water to drain into the soil). While this problem is important to practicing urban planners and ecologists, it also provides a valuable context for learners new to those fields. Key reasoning practices found in these disciplines are described below.

Spatial Reasoning in Environmental Science and Urban Planning

Planners argue for the importance of spatiotemporal context and place-based analysis in their research. These tasks draw on planners' ability to think spatially. Spatial thinking in the social sciences generally demands a simultaneous integration of multiple spatial concepts. In Table 1 we build on five general spatial skills identified by Janelle & Goodchild (2011), who situated these skills in the context of practice. Column 1 lists the general skills, while Column 2 provides examples of areas where those skills would be used in UP and ES. A host of other researchers (Golledge, 1995; Janelle & Goodchild, 2011; Jo & Bednarz, 2009; Kaufman, 2004), however, have also produced categorizations and ontologies of spatial skills, which we use to identify component skills in Column 3. Column 4 then illustrates where those component skills would arise in UP and ES.

Table 1: Illustration of how general spatial skills can be broken into component skills

General spatial skill (Janelle & Goodchild, 2011)	Example skill application areas, for UP and ES	Generalized component skills	Examples of component skills in use in UP and ES
1. Detect changes in the uses of, and regional differentiation of, spaces	Differentiating: **ES**: habitats **UP**: land use, e.g., agricultural, residential	The ability to define a set of salient variables, based on the phenomena of interest, with which to differentiate space into different areas	Satellite imagery and maps are often used to determine boundaries, but one must: **ES**: select habitat factors and cutoff points (e.g. % tree coverage that counts as habitat) relevant to species of interest **UP**: define properties (e.g., types of residences) and proportions that distinguish urban from exurban land use
2. Measure the physical arrangement and clustering of phenomena to identify spatial patterns	Identifying: **ES**: nest patterns **UP**: settlement patterns	The ability to differentiate areas (see above) and to perceive their relative position; adapt concepts of distance and connectivity to context; qualitative language for patterns	A distance that permits two areas to be "connected" can be influenced by: **ES**: the foraging range of species of interest **UP**: the type of a road (highway, surface street)
3. Document spatial patterns over time to infer processes	Documenting: **ES**: invasive species spread **UP**: urban sprawl	The ability to recognize and distinguish among different spatial patterns (see prior general skill), to associate different patterns with aspects of dynamic process, and to design consistent measurement schemes to track patterns of interest; integrate analysis of both relative and absolute location	Both UP and ES have been hampered by inconsistent schemes for measuring patterns. For example, over the last 30 years: **ES**: National Land Cover Data set (NLCD) has changed land cover definitions **UP**: Land use definitions (especially "urban") have changed
4. Study flows between specific locations as indicators of spatiotemporal interactions	Studying: **ES**: genetic drift **UP**: traffic flow	Spatial dependence: the ability to integrate understanding of a dynamic process with an understanding of how spatial locations attenuate that process; the ability to map key steps in process to key locations	**ES**: Studying migration of genes across landscape as an indication of how connectivity of habitat may have changed **UP**: Studying road congestions as an indication of the interaction between signal light timing and vehicle acceleration
5. Measure spatial associations (and space-time associations) to test hypotheses	Investigating: **ES**: effect of habitat features on organisms **UP**: effect of zoning on land use	A sense of time scale and spatial scale magnitudes, and quantitative metrics for measuring spatial properties and patterns	**ES**: Test if connectivity affects rate of genetic drift by measuring genetic diversity over time as habitat pattern changes **UP**: Test if zoning affects land use by measuring density of development in zoned and unzoned areas over span of 10 years

Engaging in the spatial reasoning processes outlined above entails integrating a number of component spatial skills, many of which involve making nuanced judgements about spatial concepts. For example, although the concept of a “habitat patch” may be simple, operationalizing it in a spatial sense requires judgements about spatial “cut off” points, among other distinctions. While these judgements are certainly guided by the topic of interest (e.g., a specific species of animal, or certain impacts of land use), even experts recognize that these decisions are not objectively certain. It is just this sort of practice with making critical, qualitative judgements (“reasoned guesses”) that has been lacking in traditional STEM curricula, and whose lack often renders recent STEM graduates paralyzed when confronted with real-world ambiguity. Learning how to approach a problem space that requires such judgements, learning to not be paralyzed by uncertainty, but also recognizing that other judgements could have resulted in alternate results and remaining open to other problem formulations are part of authentic practice in these domains. While this is impossible to fully address in our study without a structured curriculum, extended time, and other supports, we do wish to discover how learners differentiate spatial regions based on the salience of observed characteristics (general skill 1), perceive and describe patterns (general skill 2), and test hypotheses by measuring spatiotemporal associations (general skill 3).

Wicked Problems

An important component of the planning and policy practices described above is the necessity to make consequential decisions when there is inadequate, conflicting, or changing information. This particularly complex quandary is known as a wicked problem (Rittel & Webber, 1973). Wicked problems—in contrast to "tame" or "benign" problems that may be difficult, but are definitely solvable—cannot be clearly defined or solved, resist objective judgment, and are unique and nested in larger issues, among other qualities. In this way, wicked problems share some similarities to ill-structured problems. Ill-structured problems don’t have a positive definition, however, but are instead defined in relation to well-structured problems, which have single solutions, optimal solution paths, and structured goals (Sinott, 1989). By contrast, ill-structured problems have unclear (and possibly multiple) solutions, although the mechanisms used to solve both classes of problems are thought to be the same (Simon, 1973). Wicked problems similarly have multiple possible solutions, no clear optimal solution path, and ill-defined goals. Wicked problems differ from ill-structured problems in three main ways, however: (1) wicked problems emphasize the importance of *context* in shaping the goals, solutions, and solution paths, meaning that solution strategies developed for one context may not be applicable to another context; (2) wicked problems stress the *consequentiality* of solutions on the real world, meaning that problem solvers are asked to take stances on values and morality in order to define goals; (3) wicked problems are *collective* in that the values and morality incorporated into goal definitions are informed by a range of diverse stakeholders (Munneke et al., 2007). These differences suggest that what is known about ill-structured problem solving strategies may not be sufficient to understand how to support learners as they attempt to solve wicked problems.

When planners attempt to solve wicked problems, they must have the ability to frame and define problem spaces, identify possible goals and solutions in those spaces, enact procedures to reach those goals, and do all of these in a way that fits real-world constraints. With the short, 2-year professional training planners receive, they cannot practice exercising these skills enough to adopt them as part of their standard practice (Zellner & Campbell, 2011). Clearly, planners need earlier and more frequent exposure to these problem spaces, but others would benefit as well. Incorporating wicked problems into public education would better prepare future stakeholders for participating in the planning process, because stakeholders must ultimately buy into the tradeoffs inherent in plans for those plans to succeed. Thus, the wicked problems selected for incorporation into curricula should have relevance for both future planners and future stakeholders.

For our study, we chose the domain of stormwater management, which is a planning problem that urban and suburban residents find relatable. This problem domain also has relevance to environmental science. Stormwater management (especially in urban areas) requires spatial specificity incorporating both human and natural systems, and has direct consequences on city residents and other stakeholders. Working with this rich domain, we decided to focus on how it could be used to highlight a subset of the reasoning required for dealing with wicked problems. The accessibility of the stormwater management domain allows us to gradually introduce novice learners to reasoning about wicked problems, with the goal of starting learners on the progression towards developing the skill of compromising across competing definitions and demands. This is similar to Songer’s (2006) BioKids curriculum, which similarly repackages professional-level concepts into a learning progression more suitable to novice learners.

Complex Systems Models as Tools for Exploring Wicked Problems

Complex systems simulations are an existing approach for presenting domain-specific and real-world phenomena to learners (Goldstone, 2006). These simulations are dynamic, centrally rely on iteration and feedback, and are made up of many parts organized across multiple levels of scale. As such, these tools provide a new opportunity for confronting aspects of wicked problems otherwise considered intractible. For example, when Rittel & Webber (1973) conceptualized wicked problems, they assumed that any exploration of the problem space would take place in the real world. With complex systems simulations, practices that Rittel & Webber advocated against (e.g. experimenting with different strategies, examining multi-level interactions) are instead sources of explanatory power (Zellner & Campbell, 2011).

Learners are being provided with new tools that represent the spatial and dynamic interactions that underlie wicked problems in urban planning and environmental science, allowing learners to reason about these problems in a different way than they could without modeling and simulation software. This contrasts with common school practices, which prioritize correct answers over exploratory processes, often fail to link classroom activities to real-world practices, and mainly deal with well-defined problems and procedures. This exacerbates students' inability to deal with wicked problems by giving them practice in exactly the wrong skills. One value of complex systems simulations lies in their ability to help users recognize how spatial and dynamic interactions lead to the emergence of wicked problems, which allows them to explore a richer range of solutions. The tools also allow learners to actively explore the different tradeoffs involved in solving wicked problems. This exploration forces learners to voice and test their hidden assumptions, leading to the collective definition of values that is necessary when grappling with wicked problems.

Prior Work

Learning Technologies Applicable to Wicked Problems in Urban Planning and Environmental Science

Technological capabilities for scaffolding spatial thinking have been developing faster than our understanding of the acquisition of skills in fundamental spatial thinking (Janelle & Goodchild, 2011). Geographic information systems (GIS) are heralded as a potentially effective tool for teaching basic spatial concepts in K–12 classrooms (NRC, 2006). However, when implemented in their current state in classrooms the risk may become one of teaching ''buttonology,'' or point-and-click procedures, to obtain a specified outcome (Marsh, Golledge & Battersby, 2007). With the buttonology approach, learning how to use the software program often supercedes conceptual and procedural understanding of the spatial analysis the software program is performing. Some packages, like MyWorld (Brown & Edelson, 1998) intentionally simplify the interface to re-align focus on the critical concepts and content (e.g., global earthquake data). We are taking a similar approach by adapting complex system models designed for use by environmental scientists and urban planners.

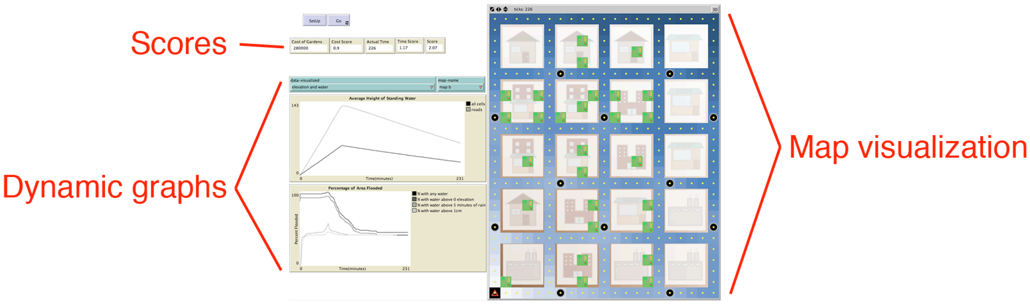
Researchers have studied introducing learners to complex systems perspectives, which typically addresses how complex science content should be structured (e.g., Liu, Marathe, & Hmelo-Silver, 2005) or how to regulate students' learning about complex systems (e.g., Azevedo et al., 2004). Such ideas will influence us as we structure our curriculum in the future, but perhaps more relevant to this study is work exploring how ABMs can be used to teach complex systems principles (e.g., Wilensky & Resnick, 1999; Goldstone, 2006). What distinguishes our work from theirs is that we are not trying to induce students to understand basic principles like "emergence" – rather, we are using these tools to help students confront compromise.

Activity and Study Design

The original stormwater management model (*L-GrID*) was designed to allow researchers to investigate the impact of different types of ground cover on groundwater infiltration. To adapt it for use with novices in fifteen-minute sessions we had to scale back the detail made apparent to the user. We reduced the types of ground cover to three: impermeable (road surfaces), highly-permeable (swales) and semi-permeable (non-road patches that were not yet converted to swales). Additional simulation elements included sewers (which drain water from surrounding patches), elevation (the map sloped from a high at the top right corner to a low at the bottom left), an output sink (at the lowest corner of the map), and rain (set to always reproduce a devastating "hundred year" storm). We presented different contexts by varying sewer placement and ground cover across three maps encountered by learners. We reduced the outputs of the simulation to two: infiltration speed (time taken to clear all of the storm's water from the map) and cost (each swale cost "$10,000"). Users could move and place swales on patches of the map, hit "go", and witness how their configuration affected both the score-based outputs (cost and infiltration) as well as view a visualization of the depth of the water as it flowed across the map.

We recruited fourteen pairs of undergraduates (as proxies for high school seniors). Because this was a lab-based pilot study, to encourage them to take the problem solving task seriously we borrowed from methods used in experimental economics. The ABM was structured to use the two simulation outputs (cost and infiltration) as two competing reward functions, and the cash payout participants would receive could be improved upon by optimizing across these two reward functions. To avoid discouraging them from exploring the problem space, the final reward was based on the best score they were able to attain within the allotted time of 15 minutes. We recorded video, transcribed their conversations, and collected data on the scores they attained with each trial.

This stormwater management task gives learners the opportunity to engage with the aspects of wicked problems that are not always addressed by ill-structured problem solving tasks (*context*, *consequentiality*, *collectivity*). The two monetary reward functions are simplistic placeholders for the values of different stakeholders. Learners must determine how to reconcile the scores produced by these functions, which drives further exploration of the problem space. This reconciliation process is an entry point for novices to confront the demands of *consequentiality* and *collectivity* involved in solving wicked problems. Furthermore, by exposing learners to multiple maps which—despite surface similarities—demand different approaches to swale placement, we highlight that the *context* shapes the selection of heuristics for solving wicked problems.



Cost of Gardens: 280000
Cost Score: 0.9
Actual Time: 226
Time Score: 1.17
Score: 2.07
data-visualized: elevation and water
map-name: map b

Figure 1. Screenshot of the GI ABM used in this study, adapted from a more extensive *NetLogo*-based model built by the co-PIs for the Illinois EPA-funded *Green Infrastructure Plan for Illinois* project.

Coding Schemes

The literature on problem solving has codified several common strategies, labeled “weak problem solving strategies” (Simon, 1978), that learners use when confronting ill-structured problems (e.g. analogy, hill climbing, generate-and-test, means-ends analysis, problem decomposition, problem conversion). However, these strategies were deduced from studies with individual learners, and thus may not encompass the full range of strategies we expect to see during wicked problem solution. In particular, the properties that distinguish wicked problems (context, consequentiality, collectivity) place special emphasis on evolving a collectively acceptable goal definition that fits a particular set of circumstances. This change in emphasis necessitated an emergent coding approach (Strauss & Corbin, 2008) to identify the kinds of strategies used by our participants.

The strategy kinds we identified each describe a particular form of shared, sustained discussion or work on the model. These included budgeting the total amount of gardens used (*formal budgeting*), adding or removing a nonspecified number of gardens (*informal budgeting*), focusing on particular large (map-wide) or small (block- and road-level) scales (*large- and small-scale spatial*), reacting to the spatial dynamics of the last run of the simulation (*reactive spatial*), and exploring garden-placement maxima and minima (*determining limits*). Three strategies we identified correlated with higher scores, or were used more often (see Table 2).

A *formal budgeting* strategy was defined as the pair of learners setting a shared cap on the number of gardens used. This strategy was unsurprisingly associated with better performance on our cost score metric, although the budgets we observed were seemingly arbitrary. For instance, they tended not to stray from a restricted band of values (a cap of around 20 gardens). Despite a surface similarity to a means-end strategy (Simon, 1978), we did not observe learners justifying their budget. This indicates that learners need to be scaffolded to explore a wider range of budgets which would have a more principled effect on cost score.

Table 2: Average scores per trial and frequency of use for observed strategies.

	Reactive Spatial	Formal Budgeting	Informal Budgeting	Determining Limits	Large-Scale Spatial	Small-Scale Spatial
Avg. Cost Score	0.97	1.03	0.94	0.88	1.01	1.01
Avg. Infiltration Score	0.50	0.34	0.53	0.56	0.42	0.42
Avg. Overall Score	1.47	1.37	1.46	1.43	1.43	1.43
% Freq. of strategy use	26.31%	6.88%	14.55%	3.33%	30.86%	13.78%

With regards to the infiltration score, learners were most effective using a *reactive spatial* strategy, so named because it involved incremental changes based on the visualization. Users would point out spots of the map where water flow slowed or stopped, and would accordingly shore those up with gardens or attempt to restructure their arrangement to guide water in different ways. An exemplar of hill-climbing (Simon, 1978), using a reactive spatial strategy was effective in incrementally improving the infiltration score, but not as effective as the *determining limits* strategy. This suggests that learners need to better identify which parts of the map are critical, which is tied to detection of potential changes in the use of space (Janelle & Goodchild, 2011).

Unlike the prior strategies we identified, the *small-* and *large-scale spatial* strategies were not so much related to problem solving heuristics as they were descriptive of the spatial reasoning of learners. It is also significant that the majority of learners began their interaction with the model by using a *large-scale spatial* strategy (see Table 2), which involves learners selecting and working on large regions of the map (usually described by learners in cardinal or relative directions, e.g., north/south, up/down, left/right). This stands in contrast to the relative paucity of *small-scale spatial* strategies, which would involve attending to small-scale features (e.g., adjacency and relative distance of map elements). Adjacency and distance can in fact strongly affect flooding, so learners require support to notice partitions of space (general skill 1) and their relations to one another (general skill 2), and to transition between different granularities of scale (general skill 5) (see Table 1). This could be accomplished through instructional support that identifies domain-meaningful distinctions amongst regions that users could choose to adopt.

Case Studies

Case 1: Learning to compromise takes more than heuristics

In this section, we highlight group conversations that show engagement with compromises between competing reward systems – i.e, showing how they responded to the characteristic lack of true or false answers to wicked problems. The two reward systems highlighted in our experimental trial were cost reduction (the players were penalized for the cost of installing each green infrastructure garden), and rate of rainwater infiltration (the players were rewarded for reducing the time taken for rainwater to drain). These two reward systems combine to form an overall score – although it should be emphasized that these reward functions are often competing: more gardens improve infiltration, but also increase the overall cost, and vice-versa. Moreover, the specific spatial arrangements of the gardens can also affect their infiltration efficacy. The following conversations have been selected from two groups of students to illustrate the types of discussion about compromise that occurred.

In one group, S17 and S18 have just completed a garden arrangement and are watching the simulated outcome. They discuss their next strategy, balancing an observation that a larger number of gardens was helping them do well on infiltration against the observation that the cost was prohibitive:

S17: We're doing well. Is the answer more gardens?
S18: Oooh, arright. Where's the drainage seem to be caught, though?
S17: It’s going a lot faster, but it’s the garden cost, is, uh, kinda screwin’ us over
S18: Well, you can remove—I wanna remove this one. Maybe we could put two down here, maybe

S17’s observation of the decrease in cost score shapes the subsequent strategy. They attempt to balance these competing rewards and achieve an alternative solution in the problem space as they have constructed it. Their approach is incremental (“this one”, “we could put two”), suggesting that it did not occur to them that they could use a means-end strategy, working backwards from the desired cost score increase to determine the number of gardens to target for removal. Another group, however, showed a much more sophisticated approach. Initially, students S19 and S20 are trying to figure out their first garden-placement move, and seem to only consider the rate of infiltration (which they refer to as the “time score”):

S20: In theory you should probably want to have more, uh, more sinks for the water up at the top, because that's where the source of them
S19: Right
S20: But, if you have them towards the bottom, then it would drain out the entire area probably more effectively
S19: But in order to keep the time score low, maybe we should have some at the top and some at the bottom?
S20: Um, let's see
S19: To prevent all of the water from rushing down
S20: Let’s see, so the top drains out first

Their initial strategy is to consider the infiltration pattern of the given map, by “study[ing] flows between specific locations,” (general spatial skill 4, see Table 1). They discuss whether it would be more effective to place gardens near the high elevation region (they mistake it as the “source” of the water) or near the main outflow at the bottom of the map. Later, after watching the simulation run their arrangement, they incorporate the reward structure of garden cost:

S20: I think we're, uh, seeing cost score coming—going—go down pretty quickly, so…
S19: /Yeah
S20: …that may mean we're—we're, uh—we're adding few
S19: We're getting a good return on, uh, on the gardens. Um, but we're still not anywhere near 2.25
S20: Yeah, let’s see
S19: If we have—if we're getting a good return on the gardens we have, but we're ideally looking for a score that's…

S20: /Probably around 2?
S19: Yeah, I mean 2.25 is the ideal
S20: Yeah
S19: I think we could probably have—20 gardens—on there, and still get a fairly good overall score. And a good return on gardens

S19 and S20 not only identify the competing reward structure and factor it into their decision making process, but they actually generate an entirely new construct: "good return" on the gardens. The language they use here indicates that they are embedding cost and infiltration not as independent factors, but as unified ratio – a tradeoff. Unsurprisingly, it is after this discussion that S19 and S20 achieve their highest combined score. In their reasoning they also use the "ideal" score (what one could earn with maximum infiltration and no gardens, an impossibility) as an anchor point to work backwards from, in order to make judgements about how many gardens they can add without a significant hit in cost score.

From these cases it is evident that while students are thinking about the competing reward structures without any explicit external prompts, this alone is not enough to guarantee success. The pattern exemplified by the first group (S17 and S18) shows a tendency to vacillate between first trying to satisfy one constraint, then the other. While this generate-and-test strategy can result in improved scores, these improvements are gradual, and may not help the learners to understand the essential relationship between the reward structures. The second group, on the other hand, demonstrates what is possible when means-end reasoning can be brought to bear on the problem, and when intermediate score evaluation representations (such as ratios) can be constructed.

Case 2: Lack of consideration of distance and adjacency

The pattern of sewers on the city map is an important *small-scale spatial* feature of the problem space. If learners place the gardens relative to sewer locations, they have the opportunity to maximize infiltration with a reduced number of gardens. However, we seldom saw this occur. While sewers were spoken of in 16 out of 28 (57%) conditions, mentions of sewers were present in only 1.19% of all discussion turns, a very low rate of occurrence around the second spatial component skill of distance and adjacency (see Table 1). In groups that do talk about distance and adjacency of gardens to sewers, the idea is very shortlived. For example:

S20: What do you think—edges—or towards the, um, towards the middle? I think, um, keep 'em towards the streets, then—that's also where the sewers are
S19: Yeah, I was thinking that perhaps we should orient the gardens near the sewers, um
S20: Well then you have two sinks at the—at the same location—versus
S19: Spreading them out
S20: Yeah
S19: Yeah. Ok. Well what if we added four more gardens, umm, in this general area but not near the sewers

This conversation lasts for less than a minute, and sewers are only briefly mentioned once more towards the end of their activity. This is typical of the conversations happening in other groups, where sewers are not recurrent strategic elements. This is an example of where scaffolding to help learners attend to small-scale spatial features could assist learners to bolster their spatial strategizing.

Discussion and Conclusion

Overall, learners required more support to engage in the spatial component tasks we identified as valuable for spatial reasoning and dealing with wicked problems. In particular, we found a need to support learners as they decompose space into regions, notice patterns across regions, and apply strategies that operate across multiple spatial granularities. To afford better reasoning about wicked problems, we need to encourage learners to engage in boundary testing, as this allows them to bring other problem-solving strategies (like means-ends analysis) to bear on the problem space.

Since this study reports on a pilot of the simulation, we are in the process of developing a larger curriculum to complement this model's impact on the development of spatial reasoning and systems thinking skills. It is very difficult for learners to incorporate all elements of the model into their judgments and plans, so a curricular scaffold could allow them to better accomplish this task. By balancing the diverse inputs, outputs, and processes that make up the simulation, learners can make more intentional and justified choices to affect the model, instead of taking actions that are abitrary or needlessly restricted.

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